

Coping with drought: Options for soil and water management in semi-arid Kenya

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Table of contents

Chapter 1	Introduction	1
Chapter 2	Analysis of agricultural drought in Iiuni, Eastern Kenya: Application of a Markov model	11
Chapter 3	Tillage methods and soil and water conservation in Eastern Africa	35
Chapter 4	Tillage and farmyard manure effects on crusting and compacting soils at Katumani, semi-arid Kenya	53
Chapter 5	Influence of land use changes on watershed runoff volume: Application of AGNPS model in Iiuni watershed, Kenya	69
Chapter 6	Watershed conservation in semi-arid Kenya	89
Chapter 7	Summary and conclusions	109
Samenvatting en Conclusies		115
Curriculum vitae		119

Chapter 1

Introduction

Introduction

1.1 Semi-arid environments

Of Kenya's total land area of 582,646 km², arid and semi-arid lands occupy more than 80%. Semi-arid lands occupy approximately 30% of the total land area and are classified into two agro-climatic zones (ACZ), IV and V (Table 1), on the basis of the ratio of rainfall to open water evaporation (R/E_o). The two agro-climatic zones have a ratio of 25% to 50% and a medium to low potential for plant growth and a high risk (25%-75%) of crop failure (Sombroek et al., 1982). Annual rainfall in the two zones ranges from 900 mm in ACZ IV (transitional zone) to 450 mm in ACZ V (Table 1).

Table 1. Agro-climatic zones of Kenya, excluding areas above 3000 m altitude (Sombroek et al., 1982).

Zone	R/E_o † (%)	Classification	R (mm)	E_o (mm)	Potential for plant growth‡	Risk of crop failure
I	> 80	Humid	1100-2700	1200-2000	Very high	Extremely low (0-1%)
II	65-80	Sub-humid	1000-1600	1300-2100	High	Very low (1-5%)
III	50-65	Semi-humid	800-1400	1450-2200	High to medium	Fairly low (5-10%)
IV	40-50	Semi-humid to semi-arid	600-1100	1500-2200	Medium	Low (10-25%)
V	25-40	Semi-arid	450-900	1650-2300	Medium to low	High (25-75%)
VI	15-25	Arid	300-560	1900-2400	Low	Very high (75-95%)
VII	< 15	Very arid	150-350	2100-2500	Very low	Extremely high (95-100%)

†R - average annual rainfall; E_o - average annual evaporation.

‡Assuming that soil conditions are not limiting

The rainfall patterns in Kenya are governed by the seasonal shifts and intensity of the low pressure Inter-Tropical Convergence Zone (ITCZ). Rainfall occurrence is primarily bimodal with two distinct rainy seasons, the short and long rains. Rainfall peaks in November during the short rains and in April during the long rains. About 90% of the total annual rainfall occurs in the two rainy seasons. In semi-arid Kenya, the short rains (October to December) are more reliable, evenly distributed and adequate for crop production. The long rains (March to May) are associated with most crop failures due to the poor distribution, unreliability and inadequacy for crop production (Biamah et al., 1993).

For cereal crops, rainfall amounts are on average too low for optimal crop yields, and season-to-season rainfall variability is high. Prolonged dry spells during the rainy seasons often lead to food, forage and water shortages. The very high soil moisture deficits experienced in these zones usually result in significant decreases in agricultural production.

The most dominant soils in the Kenyan semi-arid areas are Luvisols, Lixisols, Acrisols, Alisols, Ferralsols, Planosols, Solonchaks, Solonetz, Vertisols and Fluvisols (FAO/UNESCO Classification). The Acrisols, Alisols, Ferralsols and Planosols are predominant in highland areas. Whereas the Luvisols, Lixisols, Solonchaks, Solonetz, Vertisols and Fluvisols are found in lowland areas. These semi-arid soils are considered to be problematic, because their physico-chemical properties limit the uses for agricultural purposes. They generally have low organic matter contents and an unstable structure (Biamah et al., 1994). The main problems associated with these soils are high levels of salinity and sodicity, poor drainage, soil erosion, soil compaction, soil crusting and low soil fertility (Biamah et

al., 1994). Surface crusting properties are enhanced by rainfall of high intensity and short duration that is prevalent in semi-arid Kenya. Crust formation is caused by the breakdown in soil aggregates and the dispersion of clay after getting exposed to the beating action of raindrops (Biamah et al., 1993).

The Luvisols, Lixisols, Acrisols, Alisols and Ferralsols are characterized by poor structural stability of the surface soils, which have surface crusting properties and often result in low infiltration rates and high susceptibilities to erosion. The occurrence of hardpans in the subsoils leads to low porosity and reduced water holding capacities. The Solonchaks (saline) and Solonetz (sodic) soils are characterized by poor structure and low infiltration rates. Most of the areas with these soils are severely degraded (Biamah et al., 1994).

Other soils that occur in limited patches in semi-arid Kenya are Fluvisols and Vertisols. They occur mainly in floodplains and depressions. Vertisols due to their heavy clay content are often avoided because they are hard to plough using traditional tillage practices (conventional ox or donkey ploughing). Another constraint to the utilization of Vertisols is their high salinity/sodicity (Biamah et al., 1994).

Most of the problems associated with semi arid soils have in the past been overcome through the traditional shifting cultivation. However, this farming practice is increasingly becoming ineffective and unsustainable as continuous cultivation and associated nutrient depletion become common (Bekunda et al., 1997; Sanchez et al., 1997).

1.2 Agricultural drought

Available soil moisture within the root zone and the actual evapo-transpiration, which responds to the changes in soil moisture content, are the two parameters of the soil water balance that will influence the occurrence of water stress in rainfed agricultural systems. An agricultural drought occurs when extended periods (days) without rainfall are experienced and the crop water requirements (potential evapo-transpiration) exceed the available soil moisture within the crop rooting zone. Seasonal changes in available soil moisture result in agricultural droughts of varying magnitudes. These fluctuations in soil moisture often extend to critical crop growth periods and hence affect crop productivity significantly. Other factors that are critical to crop production and that are affected by the duration of the dry spells are: antecedent soil moisture, the water storage capacity of the soil within the crop rooting zone, and the water requirements of the major crops (e.g. maize, beans, sorghum and millet).

Agricultural droughts that occur in semi-arid Kenya, vary in duration and severity with the prevailing agro-climatic conditions as reflected by seasonal rainfall variability. Rainfall distribution varies with the duration of the short rains and long rains. From an analysis of rainfall data from Iiuni watershed at Machakos, Kenya, the average seasonal rainfall durations are twelve weeks for the short rains and ten weeks for the long rains. The period of cessation of rains starts when a trend of persistent one rain day per week is experienced and the daily rainfall is much less than the expected daily potential evapo-transpiration rate (Biamah, et al., 1998).

According to Biamah (2001), the long-term seasonal drought patterns in semi-arid Kenya show a trend of more deficits (dry spells) than surpluses (wet spells). This trend also varies with the rainy seasons. For instance, there are more dry spells in the long rains (March to May) than in the short rains (October to December). The strong variability of rainfall from year to year and season to season

makes it necessary to use long-term data to obtain meaningful drought trends. A period of about 30 years must be considered the absolute minimum for a rainfall event analysis (Nieuwolt, 1978).

1.3 Agricultural crop production

The major staple food crops grown in semi-arid Kenya include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cowpeas, pumpkin, and groundnuts. The cash crops include cotton, sisal, and tobacco. Crop performance and yield are significantly influenced by the amount of rainfall and distribution throughout the rainy season. As a result of inherent soil moisture deficits, the period of cropping is limited to the two rainy seasons. The potential length of the growing season differs for the long and short rains, and influences the choice of crops. Most crops are grown during the short rains, since rainfall is more reliable in this period. Inter-cropping of legume cover crops (e.g. beans and peas) with maize is a common farming practice as it minimizes risks of crop failure due to unexpected soil moisture deficits. Extensive mixed cropping (without crop rotation) is practiced as a risk spreading strategy. In the floodplains, where the water table remains high and there is adequate soil moisture, crops like bananas, sugar cane and vegetables are grown (Biamah et al., 1993).

Rainfall effectiveness is a critical factor influencing crop productivity. For example, during the short rains in Katumani, Machakos, an effective rainfall of 230 mm is required to produce a minimum yield of 1.5 ton of maize. The maximum maize yield (7.8 to 8.4 ton per hectare) requires 350-460 mm of effective rainfall. Likewise in the long rains, an effective rainfall of 170-180 mm is required to produce a minimum yield of 1.5 tonnes of maize per hectare. The maximum maize yield (4.8 to 7.2 ton per hectare) requires 280-440 mm of effective rainfall (Stewart and Harsh, 1982).

In semi-arid Kenya, the major constraints for agricultural crop production are accelerated soil erosion, induced soil moisture deficits, soil fertility depletion, and soil crusting and compaction (Biamah et al., 1998). These problems are stratified according to slope, agro-climatic zones, soil types and land use. In upland areas, major problems are soil erosion and low soil fertility. In lowland areas, the main problems are insufficient soil moisture, soil crusting and compaction (Biamah et al., 1998). The soil crusting and compaction problem is attributed to inherent soil properties and poor tillage practices. Tillage using the wrong implements and when done on moist or wet soils is known to cause the development of subsurface plough pans. These hardpans affect root penetration, rainwater infiltration and soil moisture storage capacity (Biamah et al., 1993).

The management options for crop production in semi-arid Kenya vary with soil type and their specific problems (Table 2). An understanding of land management problems on the different soil types is necessary before recommending suitable conservation techniques.

The tillage and residue management practices that are suitable for agricultural drought mitigation in semi-arid Kenya can be broadly grouped under conservation tillage. Conservation tillage creates a suitable environment for growing a crop and conserves soil, water and nutrients. Ideally, conservation tillage per se excludes conventional tillage operations that invert the soil and bury crop residues. However in practice, conservation tillage sometimes is preceded by conventional tillage soon after the crops are harvested. Also, there is a broad spectrum of transitional tillage stages to conservation tillage. These can range from conservation tillage practices like tied ridging, preceded by conventional tillage all the way to zero tillage systems where seeds are spot planted with sticks. Conservation tillage

involves tillage practices that leave plant residues in the field and that create soil surface roughness for controlling soil erosion. Conservation tillage systems include: zero or no tillage; mulch and farmyard manure tillage; and reduced or minimum tillage (Biamah and Rockstrom, 2000).

Residue management practices are often introduced on cropland after primary tillage operations have been carried out along the contour. These practices are complementary to other tillage practices and are expected to improve soil productivity by minimizing soil crusting and compaction, improving soil fertility and soil moisture storage capacity within the plough layer (Biamah and Rockstrom, 2000).

The basic principles of sound conservation tillage practice include: (1) subsoiling to break the plough pan or ripping/chiseling to minimize soil compaction within the plough layer; (2) introduction of effective erosion control measures before tillage; (3) carrying out all tillage practices along the contour; (4) avoiding soil compaction by keeping oxen and machinery off moist/wet soils; (5) avoiding pulverization of the plough layer to prevent soil sealing and crusting; (6) ensuring that soil fertility is optimal before introducing any practices; and (7) recommending residue management practices in marginal rainfall areas with structurally unstable soils (e.g. sodic soils) (Biamah and Rockstrom, 2000).

Table 2. Management options for problems soils in semi-arid Kenya (Biamah, 2001).

Soil type	Management options
Vertisols	Minimize waterlogging through seasonal drainage. Discourage structural conservation measures due to unstable structure. Avoid deep tillage due to subsoil sodicity in some areas. Tillage under optimal soil moisture conditions
Planosols	Minimize waterlogging through deep tillage and artificial drainage. Improve fertility through application of FYM† and inorganic fertilizers. Ideal for shallow rooted crops and pastures for grazing. Tillage under dry conditions when workability is good.
Ferralsols	Apply FYM and chemical fertilizers to improve soil moisture retention in topsoil(s) and ameliorate the fertility problem. Tillage under moist soil conditions when soil compaction is minimal.
Fluvisols	Choose deep-rooted crops that can access fertile subsoils. Apply FYM to improve soil moisture retention in topsoil(s). Tillage under moist soil conditions when workability is good
Luvisols, Lixisols, Acrisols, Alisols	Ripping and subsoiling to improve rainwater infiltration and soil moisture storage. Breaking of soil crusts and subsurface hardpans. Apply FYM to increase infiltration, reduce surface runoff and crusting. Application of chemical fertilizers to ameliorate soil fertility problem. Tillage after harvesting when soil moisture conditions are favourable and draft power requirements are low
Solonchaks	Apply FYM to improve soil aggregation and drainage. Leaching of salts through irrigation. Planting of salt tolerant trees (e.g. <i>Prosopis juliflora</i> and <i>Sesbania sesban</i>). Application of gypsum to neutralize soil reaction.
Solonetz	No disturbance of topsoil through tillage. Diversion of concentrated runoff water flow away from exposed sodic soils. Permanent plant cover. Planting of salt tolerant trees (e.g. <i>Prosopis juliflora</i> and <i>Sesbania sesban</i>). Application of chemicals (e.g. gypsum) to neutralize soil reaction.

†FYM - farm yard manure

1.4 Research problem and aim of the study

In semi-arid Kenya, the demand for agricultural land for the ever-increasing human population has almost invariably pushed farmers into cultivation of structurally unstable soils on steep slopes. Thus, the adoption of intensive exploitative cultivation techniques has led to a rapid decline in soil and crop productivity of steep lands (Biamah and Rockstrom, 2000). This decline in soil and crop productivity has led to the frequent occurrence of agricultural droughts. The severity and duration of those droughts vary with seasonal rainfall variability and associated differential soil moisture deficits. The recurrence of seasonal soil moisture deficits is also attributed to the withdrawal of organic matter in soils and consequent reduction in soil quality.

Over the past 100 years many severe droughts were experienced in East Africa and displaced many people. During this period, it was observed that there was a higher frequency of drought occurrence during the long rains when compared to the short rains (Ininda, 1987). Given the persistence of dry spells in semi-arid Kenya, it is pertinent that an in-depth analysis needs to be done in order to understand the trends and indicators of agricultural drought. Thus, there is the need to predict the stochastic behavior of dry and wet spells so as to provide information for drought preparedness through an early warning system. The mitigation of agricultural drought in semi-arid Kenya requires strategies and technological options that focus on the improvement of soil and crop productivity.

Since most semi-arid areas of Kenya consist of approximately 30% of rainfed agricultural land (major crops are maize, beans, sorghum and millet) and 70% of dry rangeland (degraded pastures), questions arise like:

- How does seasonal rainfall variability and distribution influence the occurrence of seasonal agricultural droughts in semi-arid Kenya?
- What is the stochastic behavior of dry and wet spells in a given study area?
- Which soil types are most vulnerable to drought?
- Under the low, erratic and ineffective rainfall conditions, which tillage and residue management practice conserves the most soil moisture (in terms of available moisture for plant growth) of each soil type?
- How significant are the effects of soil crusting and compaction on the hydrologic responses of dominant soil types in semi-arid Kenya?
- Of what significance are farmers' plots, sub-watersheds and watersheds in the mitigation of agricultural drought in semi-arid Kenya?

At the field scale, tillage and residue management practices should provide adequate ground cover to significantly reduce surface runoff, enhance infiltration and soil moisture availability for crop and fodder production. Thus it is important to evaluate existing tillage practices and their effects on soil and water conservation. The most appropriate practices are those that enhance rainwater infiltration and subsequent soil water storage capacity, improve the effective use of stored water, dissipate raindrop energy of intense rainstorms, and minimize surface runoff, soil losses and evaporation water losses during the initial stages of a crop growing season when the soil is bare and subject to soil erosion. In addition, these interventions should be aimed at reducing the effects of soil surface crusting and

compaction whilst maintaining favorable soil moisture conditions during the critical crop growth periods within a rainy season.

At the watershed scale, the different land use types may have a significant impact on watershed hydrology and related erosion problems. Modeling can help to determine the effects of land use and land use changes on hydrology and erosion. Appropriate modeling enables selection of watershed areas, as well as certain land use types that require soil and water conservation. The best soil and water management practices for mitigating problem areas should be chosen on the basis of the extent of the soil erosion, soil crusting and compaction, soil fertility and soil moisture problems. It is important to get an in-depth understanding of agricultural drought and of agro-hydrologic systems responses at the micro, meso and macro scales by examining possible planning and management options for watershed conservation in semi-arid agricultural watersheds in Kenya. The focus in any agricultural drought mitigation effort should be that of improving soil and crop productivity.

The aim of the study described in this thesis was to analyze agricultural drought, and to evaluate soil and water management options and strategies for sustainable crop production in drought-prone semi-arid Kenya.

1.5 Outline of thesis

The agro-hydrologic systems approach used in this study was applied at the micro- and meso-scales. The micro scale agro-hydrologic system study was conducted on one site representative of a farmer's plot with erosion control measures in place. This experimental site was at Katumani, Machakos, and was selected because it represents the micro-scale field conditions experienced by smallholder farmers in Kenya. In this study, different tillage practices, including the use of farmyard manure, were tested on the ability to reduce surface runoff and soil loss (Chapter 4). This information is necessary in mitigating seasonal agricultural drought, which often extends to critical crop growth periods. It is this critical soil moisture occurring within a crop-growing season that significantly affects crop performance and yields. The data collected was expected to provide an understanding of the hydrologic response of crusting and compacting soils to tillage and residue management practices.

The meso-scale agro-hydrologic system study was conducted in one semi-arid watershed with erosion control measures in place. The Iiuni watershed in Machakos was selected to represent a meso-scale conservation-planning unit (Chapters 2, 5 and 6). The experimental watershed has an area of 12 km². This watershed is located in a semi-arid area with varying rainfall, soil types, physiographic units, land uses, shapes and slopes. First, this study attempted to understand agricultural drought through an analysis of the stochastic behavior of the longest dry and wet spells and largest rainfall amounts in the watershed (Chapter 2). Then, land use and land management practices were studied, and their effects on watershed hydrology were determined by applying the SCS-CN model (USDA-SCS, 1972) (Chapter 5). This was followed by an overview of possible planning and management options and strategies for watershed conservation in semi-arid agricultural watersheds in Kenya (Chapter 6). The strategies and options proposed were based on a review of tillage methods in East Africa (Chapter 3), the agricultural drought analysis (Chapter 2), the hydrologic soil responses to tillage and residue management practices at the micro-scale level (Chapter 4) and SCS-CN model predictions of watershed runoff volume (Chapter 5). Pertinent strategies explored included: understanding agricultural drought; stratification of

production zones; watershed conservation options; planning of watershed conservation and enabling conditions. The enabling conditions that are elaborated upon include agricultural policy, smallholder agriculture and public-community partnerships.

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Chapter 2

Analysis of agricultural drought in Iiuni, Eastern Kenya: Application of a Markov model

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Abstract

In semi-arid Kenya, episodes of agricultural droughts of varying severity and duration occur. The occurrence of these agricultural droughts is associated with seasonal rainfall variability and can be reflected by seasonal soil moisture deficits that significantly affect crop performance and yield. The objective of this study was to stochastically simulate the behavior of dry and wet spells and rainfall amounts in Iiuni watershed, Kenya. The stochastic behavior of the longest dry and wet spells (runs) and largest rainfall amounts were simulated using a Markov (order 1) model. There were eight rain gauge stations within the watershed. The entire analysis was carried out using probability parameters, i.e. mean, variance, simple and conditional probabilities of dry and rain days. An analysis of variance test (ANOVA) was used to establish significant differences in rainfall characteristics between the eight stations. An analysis of the number of rain days and rainfall amount per rain day was done on a monthly basis to establish the distribution and reliability of seasonal rainfall. The graphic comparison of simulated cumulative distribution functions (CDFs) of the longest spells and largest rainfall amounts showed Markovian dependence or persistence. The longest dry spells could extend to 24 days in the long rainy season and 12 in the short rainy season. At 50% (median) probability level, the largest rainfall amounts were 91 mm for the long rainy season and 136 mm for the short rainy season. The short rains were more reliable for crop production than the long rains. The Markov model performed well and gave adequate simulations of the spells and rainfall amounts under semi-arid conditions.

2.1 Introduction

Of Kenya's total land area of 582,646 km², semi-arid lands occupy approximately 30% and are a sanctuary for 25% of the human population, 40% of the livestock population, and 50% of the wildlife population (Government of Kenya, 1992). The human population in semi-arid Kenya lives below the poverty line and has no guarantee of household food security due to harsh environmental conditions. Semi-arid lands are prone to periodic and cyclic episodes of droughts and flash floods. These hydrologic phenomena are significantly influenced by the seasonal rainfall patterns experienced in semi-arid Kenya (Government of Kenya, 1992).

The climate of semi-arid Kenya is influenced by the seasonal shifts and intensity of the low pressure Inter-Tropical Convergence Zone (ITCZ). According to Stewart and Harsh (1982), semi-arid areas of Kenya receive average annual rainfall ranging between 500 mm and 900 mm. Rainfall occurrence is primarily bimodal with two distinct rainy seasons. The first rainy season (long rains) runs from March to May, with the peak rainfall in April. The second season (short rains), runs from October to December with most rainfall in November. About 90% of the total annual rainfall occurs in these two rainy seasons. In semi-arid Kenya, the short rainy season (October to December) is associated with long wet spells that are evenly distributed and hence is considered to be more reliable for crop production. Conversely, the long rainy season (March to May) is associated with short wet spells that

are sparse and hence the season is unreliable for crop production. In both seasons, the rainfall pattern is characterized as low, erratic and poorly distributed, often resulting in severe and persistent dry spells.

Soils in semi-arid areas have physico-chemical properties that limit their uses for agricultural purposes. Some of the soil problems that limit crop production are: structural instability, low organic matter content, high salinity and sodicity, poor drainage, severe soil erosion, soil crusting and compaction, and low soil fertility. Most of the soils have unstable structures with crusting, slaking and compaction resulting in reduced rainwater infiltration and increased surface runoff and erosion of unstable subsoils. Soil crusting and compaction also inhibit seed germination and root penetration of dryland crops (Biamah et al., 1993).

The climate and soil conditions in semi-arid Kenya result in a medium to low potential for crop growth and a high risk (25-75%) of crop failure (Sombroek et al., 1982). The major staple food crops grown include: maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cow peas, pumpkin, and groundnuts. The cash crops include: cotton, sisal, and tobacco. Most crops are grown under conventional tillage (ox-drawn moldboard plowing, hand hoeing) systems, which limit the tillage depth to about 10 cm. This limitation in the depth of tillage is due to the occurrence of plough and hard pans. However where conservation tillage practices have been introduced, tillage depths of 20 to 25 cm have been attained. Most farmers prefer early tillage operations and dry planting before the onset of the rains (Biamah et al., 2000).

In Kenya, the major factor that controls agricultural productivity is rainfall. Rainfall variability from year to year causes significant differences in agricultural production with frequent low yields of subsistence food crops such as maize, beans, millet and sorghum, which often results in famine (Nieuwolt, 1978). Over the past 100 years, many severe droughts were experienced in East Africa (including Kenya) and many people displaced. Some of the droughts that persisted for two or more years were 1903-05; 1911-14; 1930-33; 1949-50; 1972-74 and 1981-84. During these periods, it was observed that there was a higher frequency of drought occurrence during the long rains when compared with the short rains (Ininda, 1987).

Droughts are natural phenomena and cannot be prevented. There are however possibilities of predicting them so as to provide the necessary information for drought preparedness through an early warning system (Sharma, 1994). The analysis of drought requires long-term historical rainfall data. The strong variability in rainfall from year to year and season to season makes it necessary to use long periods of observation to obtain meaningful rainfall indices. A period of about 30 years must be considered the absolute minimum for a rainfall event analysis (Nieuwolt, 1978).

Agricultural drought is caused by insufficient rainfall and may be defined as a deficit in soil moisture that affects agricultural production over a large area and an extended period. The duration and severity of a critical agricultural drought is best described by the return period in months and expected soil moisture deficits (in relation to crop water demand). An agricultural drought month occurring at the beginning of the crop-growing season has usually more serious effects on crop response than one occurring towards the end of the crop growth period. The effects of a drought that persist for more than one month are quite severe (Ininda, 1987).

The occurrence of agricultural drought cannot be predicted with certainty and hence must be treated as random variables that can be investigated by the theories of probability and stochastic processes (Sharma, 1994). The stochastic behavior of the longest dry and wet spells can be predicted using the theory of runs (Yevjevich, 1967; 1972), Poisson distribution of the occurrence of spells,

geometric distribution of the length of spells and the Weibull distribution of the total rain (rainfall amount) in a wet spell (Sharma, 1996). These theoretical distributions have been used as building blocks for model formulation under Kenyan conditions (Sharma, 1996).

Random and Markov models have been used to simulate the longest dry and wet spells (runs) and largest rainfall amounts (total rain over a wet spell) in semi-arid Kenya (Sharma, 1996). Sharma tested the performance of the two models using theoretical distribution functions (normal, Weibull, log-normal, and gamma distributions). Sharma (1996) developed the theoretical framework for agricultural drought analysis in Kenya by testing the performance of the two models under semi-arid conditions. The results obtained showed Markovian persistence as opposed to the random occurrence of spells. Thus the random model was found to be a poor simulator of runs and rainfall amounts while the Markov model was found to be promising in simulating the length of the longest dry and wet spells (runs) and the largest rainfall amounts during rainy seasons (Sharma, 1996). A Markov chain model is a stochastic process, which develops in time so that the “future” given the “present” is independent of the past. Markov chains constitute a very useful and widely applicable class of models for a range of scientific problems. This study has attempted to apply the Markov model to a specific semi-arid area to validate the research findings obtained by Sharma (1996).

The objective of this study was to stochastically simulate the behavior of dry and wet spells and rainfall amounts in Iiuni watershed, Kenya using a Markov model. The specific objectives were: (1) to determine the characteristics of annual, seasonal and monthly rainfall influencing agricultural drought in Iiuni, Kenya; (2) to estimate the statistical parameters for predicting the cumulative distribution functions (CDFs) of spells and rainfall amounts; and (3) to simulate stochastically the longest dry and wet spells (runs) and largest rainfall amounts using a Markov model.

2.2 Methodology

2.2.1 Description of the study area

The study area of Iiuni watershed (Fig. 1) is located in a semi-arid area that is in the south-eastern part of Machakos District, Kenya. The watershed extends from west to east between longitudes 37°20'E to 37°23'E and from north to south between latitudes 1°39'S to 1°41'S (Thomas et al., 1981). It has relatively concave ridges and watercourses running in a north-westerly direction. The watershed has an area of 12 km² and is located in agro-climatic zone IV/V that is a livestock-millet zone. Of this total area, approximately 60% is agricultural land and 40% is rangeland (Biamah et al., 1998).

The mean annual rainfall of Iiuni is 851 mm and is based on 16 years rainfall data from eight rain gauge stations (Fig. 1). Rainfall is bimodal with the long rains due from March to May and the short rains from October to December (Fig. 2). Rainfall in Iiuni is characterized as low, erratic, and poorly distributed. Consequently, seasonal rainfall is ineffective and thus causing some severe soil moisture deficits and persistent dry spells. The mean annual temperatures vary from 22°C to 28°C with no frosts at night. The mean annual potential evaporation ranges from 1650 mm to 2000 mm (Biamah *et al.*, 1998).

There are three distinct physiographic units in Iiuni watershed namely: hills or uplands; colluvial footslopes and dissected river valleys or floodplains (Lesslie and Mitchell, 1979; Thomas et al., 1981).

The dominant soil types found in Iiuni include Alisols, Leptosols, Acrisols, Planosols, Cambisols, Gleysols, Arenosols, Vertisols and Fluvisols (FAO/UNESCO Classification, 1990). These soils have low organic matter contents, low cation exchange capacity and are deficient in phosphorus, nitrogen and calcium (Biamah et al., 1998).

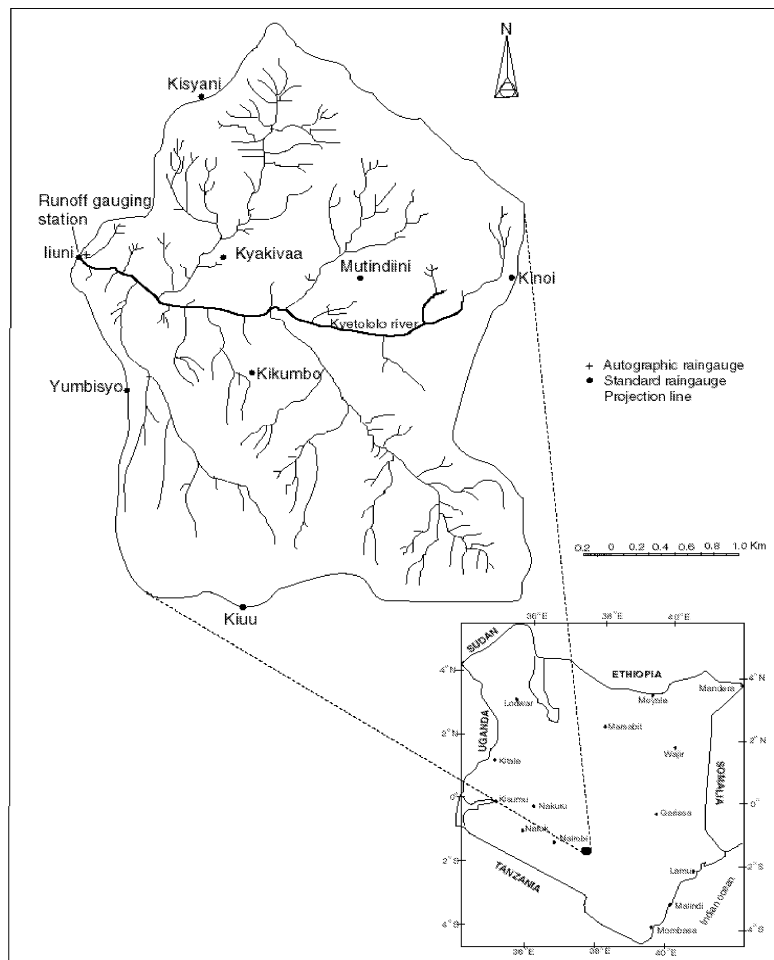


Figure 1. Distribution of rain gauge stations (•) in Iiuni watershed, Machakos District, Kenya

The major food crops grown in Iiuni include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cowpeas, and pumpkin. In the floodplains, where the water table remains high and there is adequate soil moisture, crops such as bananas, sugar cane and vegetables are grown (Biamah et al., 1998).

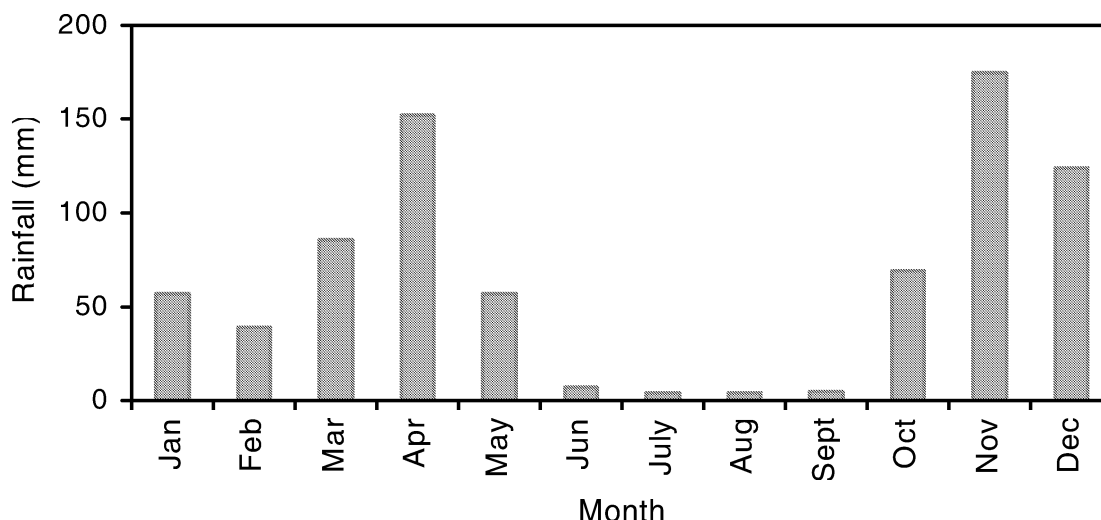


Figure 2. Mean monthly rainfall distribution of Iiuni watershed, Machakos District, Kenya.

In Iiuni watershed, the short rainy season accounts for 60% of the total annual rainfall and is the most reliable season for crop and fodder production. The long rainy season accounts for 40% of the total annual rainfall and is less reliable for crop and fodder production. The most reliable wet periods are November to mid December for the short rainy season and late March to early May for the long rainy season. Potential evapotranspiration rates during the two rainy seasons average from 5.5 to 5.9 mm day⁻¹ over a crop growth period of 90 to 120 days (Stewart and Harsh, 1982). Generally, the dry spells that are experienced in the long rainy season are more severe than those occurring in the short rainy season. During the dry spells, high temperatures above 28°C are expected and often lead to higher potential evapotranspiration rates. Thus these high evapotranspiration rates cause significant soil moisture deficits and crop water stress during crop growing seasons (Biamah et al., 1994).

2.2.2 Analysis of rainfall characteristics

Sixteen years of daily rainfall data were collected from eight rainfall recording stations in Iiuni watershed. The data were analyzed for rainfall characteristics such as: variations in maximum, minimum and mean rainfall; and variations in annual, seasonal and monthly rainfall. An analysis of variance (ANOVA) test was conducted to establish if there were any significant differences in rainfall between the eight stations. The ANOVA was done using annual and seasonal rainfall data. An analysis of the number of rainy days and rainfall amount per rain day was done on a monthly basis to establish the distribution and reliability of rainfall within the short and long rainy seasons.

For the stochastic drought analysis, there was the need to identify a rainfall station with a long-term rainfall record and yet displaying similar characteristics as those of Iiuni watershed. It was found that Kibwezi station, which is in close proximity to Iiuni, has a database of 55 years and could be considered useful for this purpose. First, the similarity in rainfall characteristics between the two stations was determined. This analysis was done by testing the equality of means and variances of the daily rainfall data between the two stations.

Two test statistics, 't' and 'F' tests at 5% level of significance, were used to test the equality of means and variances of daily rainfall data from Kibwezi and Iiuni rain gauge stations, respectively (Steel and Torrie, 1981).

2.2.3 Stochastic analysis and modeling of drought

The occurrences and lengths of dry and wet spells (runs) and magnitudes of wet spells (rainfall amount) must be well understood in order to mitigate seasonal agricultural droughts in semi-arid Kenya. A wet spell will occur when there is an uninterrupted sequence of rainy days (Bogardi et al, 1988). Similarly a dry spell will occur when the wet spell is below some threshold crop water demand (critical soil moisture). Therefore a seasonal agricultural drought would occur if there were a number of consecutive dry spells and subsequent cumulative soil moisture deficits. The severity of a critical agricultural drought is best described by the duration in days or months and expected soil moisture deficit in relation to crop water demand.

The occurrence and magnitude of hydrologic phenomena such as dry and wet spells are largely random and hence are described probabilistically. The probability of occurrence of a wet or dry day depends on the climate of a given study area. The sequence of dry or wet days may follow some trend of persistence or may evolve randomly (Sharma, 1996). A Markov process of order one in which today's state is dependent only up to one day behind best represents the simplest type of persistence or dependence. The process displaying an insignificant level of dependence is termed random or independent process.

The probability of occurrence of spells is often considered on the basis of simple (unconditional) and conditional probabilities. For instance, let a day with rainfall more than zero be designated as a wet day (w) and one with no rainfall be designated as a dry day (d). Thus the simple probability of any day being a wet day is designated as $p = P(w)$ and that of any day being a dry day is designated as $q = P(d)$. Likewise the conditional probability of any day being wet given that the previous day was also wet is designated as $pp = P(w/w)$ and the same connotation applies to a dry day followed by the previous dry day, $qq = P(d/d)$ (Sharma, 1996).

The stochastic analysis of the longest dry and wet spells and largest rainfall amounts requires estimates of unconditional probability parameters $q = P(d)$ and $p = P(w)$; conditional probability parameters $qq = P(d/d)$ and $pp = P(w/w)$; means, $\mu = E(x)$; and variances, $\sigma^2 = V(x)$. These parameters must be estimated from a long-term historical daily rainfall database to be stable and robust (Sharma, 1996). The probability parameter values of q , pp and qq , and statistical mean, variance and standard deviation used to predict the runs and rainfall amounts were obtained from an analysis of long-term rainfall data of Kibwezi (Sharma, 1996). In Iiuni watershed, the Markov (order 1) model was chosen to analyze and simulate the stochastic behavior of the longest dry and wet spells and largest rainfall amounts.

The degree of persistence of agricultural drought is quantified through conditional probability or lag 1 serial correlation coefficient. For Markov (order 1) process, the conditional probability of any day being dry given that the previous day is also dry are not equal $[P(d/d)] \neq [P(d)]$. For a random model, the conditional probability, $P(d/d)$ equals the simple probability, $P(d)$, i.e. $[P(d/d)] = [P(d)]$. For the wet days, the conditional probability of any day being wet given that the previous day is also wet are not equal $[P(w/w)] \neq [P(w)]$ for the Markov model and are equal $[P(w/w)] = [P(w)]$ for the random model.

Before formulating the Markov model, the stochastic behavior of the spells was tested for Markovian persistence or random independence using the equality of transitional matrices approach and χ -square statistics. This analysis was done for the dry and wet spells and therefore should account for a number of parameters namely: the number of dry (N_d) and wet (N_w) spells; the length of wet (L_w) and dry (L_d) spells; the longest dry and wet spells (L_{dm} , L_{wm}) and largest rainfall amounts (S_m). The stochastic theory (Sharma, 1996) used in this drought modeling exercise is described here below.

The probabilities of rain occurrences obeying a Markov or Random process can be expressed as transitional matrices as follows:

(1) Markov or persistent process (matrix 1)

$$\begin{bmatrix} pp & 1 - pp \\ 1 - qq & qq \end{bmatrix} \quad [1]$$

where $pp = P(w/w)$ and $qq = P(d/d)$.

(2) Random or independent process (matrix 2)

$$\begin{bmatrix} p & 1 - p \\ 1 - q & q \end{bmatrix} \quad [2]$$

where $p = P(w)$ and $q = P(d)$.

The numerical values of p , pp , qq and q all lie between 0 and 1, and $p+q = 1$.

A χ -square test can be used to determine if matrix 1 is equivalent to matrix 2. If they are equivalent, then the process in question is random. For a process to be random, the calculated value of χ -square statistic should be less than 3.84 at one degree of freedom and 5% level of significance (Sharma, 1996).

In a time series plot of daily rainfall (X) versus time in days during a rainy season, spells of uninterrupted wet days ($X > 0$) and spells of uninterrupted dry days ($X = 0$) will emerge. Thus in a rainy season of n days ($n = 92$ for the short and long rainy seasons in Iuni watershed), there will occur spells of wet and dry days. The number of these wet and dry spells are designated as N_w (wet) and N_d (dry) respectively, and are given values $0, 1, 2, 3, \dots, i$. The length of run or spell, L_w (wet) and L_d (dry) take on values $0, 1, 2, 3, \dots, j$. The longest dry and wet spells and largest rainfall amounts are designated as L_{dm} , L_{wm} , and S_m .

The probability distribution of Markovian runs (dry spells) follow Poisson (Gupta and Duckstein, 1975; Şen, 1980) and geometric distributions (Şen, 1980; Kottegoda, 1980; Bogardi et al, 1988) and can be expressed by the following equations (Sharma, 1996):

$$P(N_d = i) = \frac{\exp[-nq(1-qq)] [nq(1-qq)]^i}{i!} \quad [3]$$

$$P(L_d \leq j) = 1 - qq^{j-1} \text{ or } P(L_d > j) = qq^{j-1} \quad [4]$$

where n is the sample size (number of days for the short or the long rainy season).

The longest length of dry spells (L_{dm}) can be determined by the theorem of the extremes of random variables (Torodovic and Woolhiser, 1975) which can be expressed as follows (Şen, 1980):

$$P(L_{dm} \leq j) = P(N_d = 0) + \sum_{i=1}^{\infty} P(L_d \leq j)^i P(N_d = i) \quad [5]$$

The mathematical simplification of equation (5) will lead to the following equation:

$$P(L_{dm} \leq j) = \exp[-nq(1-qq)P(L_d > j)] \quad [6]$$

As

$$P(L_{dm} = j) = P(L_{dm} \leq j+1) - P(L_{dm} \leq j) \quad [7]$$

Therefore

$$P(L_{dm} = j) = \exp[-nq(1-qq)qq^{j-1}] \{ \exp[nq(1-qq)^2 qq^{j-1}] - 1 \} \quad [8]$$

Şen (1977) has derived the following relationships for the expected values of N_d and L_d denoted by $E(N_d)$ and $E(L_d)$ for Markovian runs as:

$$E(N_d) = nq(1-qq) \quad [9]$$

$$E(L_d) = \frac{1}{1-qq} \quad [10]$$

Mean (E) and variance (V) of L_{dm} can be obtained from the following relationships:

$$E(L_{dm}) = \sum_{j=1}^n jP(L_{dm} = j) \quad [11]$$

$$V(L_{dm}) = \sum_{j=1}^n j^2 P(L_{dm} = j) - E^2(L_{dm}) \quad [12]$$

Exactly the same analysis above can be carried out for the wet spells except that subscript d is replaced by w and the parameters qq by pp and q by p . For the runs following the random process, $qq = q$ and $pp = p$.

In a wet spell analysis, an additional element that appears is the total rain, which is designated as rainfall amounts and is denoted by S . Following the above analysis, the probability distribution of S_m (largest rainfall amount) can be expressed by the following relationship:

$$P(S_m \leq D) = \exp[-n p(1-pp)P(S > D)] \quad \text{for } 0 < D < \infty \quad [13]$$

where n is the sample size (number of days for the short or the long rainy seasons). $P(S \leq D)$ is the probability of a rainfall amount being less than or equal to a particular value D (say 20, 200,.....400 mm).

The probability distribution of S follows a Weibull distribution (Benjamin and Cornell, 1970; Miller and Freund, 1985; Bonacci, 1993; Sharma, 1996) and therefore the following relationships (Haan, 1977) hold:

$$P(S \leq D) = 1 - \exp \left[- \left(\frac{D}{B} \right)^A \right] \quad [14]$$

or

$$P(S > D) = \exp \left[- \left(\frac{D}{B} \right)^A \right] \quad [15]$$

The parameters A and B for the Weibull probability distribution function (PDF) can be estimated using the method of moments and are well documented in Haan (1977).

In order to estimate the parameters A and B of the Weibull PDF, the values of the mean, $E(S)$ and variance, $V(S)$ are needed and can be estimated using the following statistical relationships of the daily rainfall sequence (Şen, 1978; 1980; Llamas, 1987):

$$E(S) = kE(x) / p \quad [16]$$

$$V(S) = \left[\frac{pV(x) + qE^2(x)}{p^2} \right] \left[k + 2r \frac{k(1-r) - (1-r^k)}{(1-r)^2} \right] \quad [17]$$

$$r = \sin \pi(pp - 0.5) \quad [18]$$

in which r is the lag 1 serial correlation coefficient between daily rainfalls and k is the mean length of wet spell and can be obtained by the equation:

$$k = E(L_w) = \left[\frac{1}{1 - pp} \right] \quad [19]$$

The mean $E(x)$ and variance $V(x)$ can be calculated using the daily rainfall data for a season.

2.2.4 Simulation of drought

The process of simulating the spells (runs) and rainfall amounts in Iiuni watershed was done using four computer programs written in Quick Basic. The input required to run the programs was daily rainfall data. This computer simulation was done using the historical daily rainfall data of Iiuni and probability parameters of Kibwezi. The four computer programs used were as follows:

1. Program for computing statistical parameters of seasonal daily rainfall data (including zero rains) and based on a sample size of 92 days (3 months) per rainy season (short and long rains)

in Iiuni watershed. This was done using the short and long rainy seasons data and the outputs were the means, variances, standard deviations, and coefficients of variation and skewness.

2. Program for computing drought probabilities and surpluses for the two rainy seasons in Iiuni watershed. The outputs of this computation were unconditional probabilities (p and q), transitional matrices, chi square statistics, number and values of surpluses. The data obtained from these outputs included the maximum surpluses, number of dry (N_d) and wet (N_w) spells that were determined through a counting procedure from printed data. The occurrences of dry and wet spells were tested for dependence by computing and evaluating transitional probability matrix (1) against matrix (2) for equivalence.
3. Program for computing dry and wet spell length and surplus sum for the two rainy seasons in Iiuni watershed. The outputs of this computation were probability parameters q , qq and pp ; means, $E(x)$ and variances, $V(x)$ of dry and wet spell durations in days and the cumulative probabilities for dry and wet spells during the long and short rainy seasons.
4. Program for computing rainfall amount probabilities using Weibull distribution for the two rainy seasons in Iiuni watershed. The outputs of this Weibull distribution computation were the unconditional (p) and conditional (pp) probabilities of wet spells, mean - $E(S)$ and variance - $V(S)$ of the largest rainfall amounts, rainfall depths (in mm) and cumulative probabilities for the short and long rainy seasons.

The probability parameter values were estimated on a yearly basis taking into account the long and short rainy seasons. Thereafter, the estimated values of q , pp and qq were ranked for each season and median values used in equations 1 to 19. Values of $E(x)$ and $V(x)$ were estimated using all 55 years of daily rainfall including zero values (Table 5). The $E(x)$ and $V(x)$ were based on $n \times 92$ data points for the long and short rainy seasons. Iiuni data were used to compute probability parameter values of q , qq and pp by a counting procedure in order to test if the runs and rainfall amount are Markovian or simply random using a chi-square statistic approach. Thus matrices for each season were computed. There were 16 matrices for the short rainy season and 16 for the long rainy season.

Values of $P(S_m < D)$ were computed by assigning D equal to 0 – 400 mm and with a step of 10 mm. The upper limit of D equal to 400 mm was based on the highest seasonal rainfall expected over a long period of time (say 100 years or so) in Iiuni watershed.

During the computer simulation, Kibwezi probability parameters were used with Iiuni daily rainfall data to generate the cumulative probabilities of the runs and rainfall amounts during the short and long rainy seasons and hence were treated as predicted data. The Iiuni probability parameters, that were computed by a counting procedure, however were used to generate cumulative probabilities of the runs and rainfall amounts during the two rainy seasons and hence were treated as observed data. For each season, the length of the longest dry and wet spells and the largest rainfall amounts (i.e. 16 values of the longest runs and largest rainfall amounts) were obtained. These values were ranked by the Weibull method of frequency plotting (i.e. $F(x) = [(n+1-z)/(n+1)]$ where $F(x)$ is the cumulative probability, z is the rank in ascending order, and n is the sample size (16 in this case). The observed CDFS so obtained were graphically plotted along with the predicted CDFS (Figs 3, 4 and 5). Thus the observed CDFS were validated against the predicted CDFS through inferences on Markovian dependence.

2.3 Results and discussion

2.3.1 Characteristics of watershed rainfall

The mean annual rainfall in Iiuni watershed (based on 16 years rainfall record) of the eight rainfall recording stations was 851 mm with a station rainfall range from 778 mm (Iiuni Station) to 923 mm (Kinoi Station). During the sixteen years of rainfall record, mean annual rainfall amounts were below the mean in seven years. The coefficients of variation (CV) of station rainfall ranged between 20% to 25%, which shows that the variability in rainfall amounts between the eight stations is low. Table 1 below shows the annual rainfall data (mm) for 16 years from the eight rain gauge stations.

A one-way ANOVA was carried out to establish if the rainfall at these eight stations belongs to the same population. This analysis (Table 2) shows that there are no significant differences in rainfall between the eight rain gauge stations and therefore one station's rainfall could be considered as representative of Iiuni watershed.

In Iiuni watershed, the short rains bring about 453 mm (53%) and the long rains about 320 mm (38%) of the total annual rainfall (851 mm). Hence about 91% of the total annual rainfall occurs in the two rainy seasons. During the two rainfall periods, the coefficients of variation ranged between 30% to 37% (short rains period) and 41% to 53% (long rains period) (Table 1). Owing to this variability of seasonal rainfall, drought periods will occur even when seasonal rainfall averages are high.

Table 1. Annual and seasonal rainfall data (mm) for 16 years (1978-1993) from eight rain gauge stations at Iiuni watershed, Machakos District, Kenya.

Rainfall	Property	Stations								Mean
		Iiuni	Yumbis	Kisyani	Kinoi	Kyakiv	Mutindi	Kikum	Kiu u	
Annual rainfall	Max.	1032	1040	1162	1238	1174	1191	1210	120	1118
	Min.	310	391	324	575	365	330	324	2	382
	Mean	778	798	885	923	820	857	850	433	851
	CV†	0.22	0.22	0.23	0.20	0.25	0.24	0.25	897	0.22
										0.24
Long rains	Max.	475	526	584	564	476	548	586	655	517
	Min.	42	51	55	75	54	65	53	97	61
	Mean	278	304	327	353	302	311	353	335	320
	CV	0.53	0.48	0.50	0.41	0.47	0.48	0.51	0.47	0.48
	% Ann. mean	36	38	37	37	37	36	41	38	38
Short rains	Max.	760	721	879	864	673	614	730	751	747
	Min.	194	139	203	207	141	145	144	162	167
	Mean	431	411	488	495	434	449	454	465	453
	CV	0.35	0.35	0.37	0.36	0.34	0.30	0.31	0.33	0.34
	% Ann. mean	56	51	56	52	53	52	53	52	53

†CV = Coefficient of variation

Table 2. The ANOVA results for rainfall between eight rainfall stations in Iiuni watershed, Machakos District, Kenya.

Season	Source of variation	Degrees of freedom	Sum of squares	Mean square	F _{cal}	F _{tab} [†]
Annual rainfall	Stations	7	280698	40100	0.96	2.18
	Error	120	5025003	41875	Null hypothesis of no significant difference is accepted	
Long rains	Stations	7	73207	10458	0.41	2.09
	Error	112	2846807	25418	Null hypothesis of no significant difference is accepted	
Short rains	Stations	7	104341	14906	0.55	2.09
	Error	112	3045024	27188	Null hypothesis of no significant difference is accepted	

[†]Based on 7, 112 and 120 degrees of freedom at 5% level of significance.

An analysis of variance for the variability of seasonal rainfall within the eight rainfall stations was carried out using the ‘F’ test as was done for the annual rainfall (Table 2). The ‘F’ statistics for the seasonal rainfall provided similar results as those for the annual rainfall.

Thus rainfall within Iiuni watershed can be represented by the data of Iiuni station only. The analysis of dry and wet spells was therefore done using the data of Iiuni station. Moreover, the analysis of rainfall data in Iiuni watershed suggests that for semi-arid environments in Kenya with topographic variations similar to Iiuni, one rain gauge per 12 km² can be regarded as satisfactory.

The variability of mean monthly rainfall in Iiuni watershed is significantly high (Table 3). This is so even for the wettest months of November to December (short rains) and March to May (long rains). The variability of mean monthly rainfall during the drier months is significantly higher than the wet months. From this analysis, it is evident that the driest months in Iiuni are January, February, June, July, August and September. In this watershed, the threshold value for distinguishing a rainy day was daily rainfall equal to or less than 5 mm which is equivalent to the mean daily evaporation rate of 5 mm day⁻¹ for Iiuni.

An analysis of the number of rainy days and the rainfall amounts received per month was done to establish the distribution and reliability of rainfall within the short and long rainy seasons. This analysis has showed that the average number of rainy days per month during the short rains (Oct. to Dec.) varies between 3 to 11 and during the long rains (March to May) it varies from 4 to 10 days. The average number of seasonal rainy days is 21 for the short rainy season and 16 for the long rainy season (Table 3). These results show some significant monthly variability in rainy days.

Table 3. Mean monthly rainfall, rain days and rainfall depth per rain day at Iiuni watershed, Machakos District, Kenya.

Rainfall	Month												Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Mean (mm)	57	39	86	152	57	7	4	4	5	69	175	124	65
CV	1.17	1.31	0.81	0.64	0.64	1.39	1.35	1.07	1.55	0.78	0.40	0.57	0.92
No. of rainy days	3	2	4	8	4	1	0	0	1	4	10	7	4
Rainfall (mm) per rainy day	19	20	22	19	14	2	4	4	5	17	18	18	14

An analysis of rainfall data from Iiuni watershed has shown that the mean coefficient of variation of the short rains ($CV = 0.34$) is smaller than that of the long rains ($CV = 0.48$) implying that the short rains are more uniform than the long rains. The lengths of the longest dry and wet spells also confirm that the short rains are more reliable for crop production in Iiuni. The cessation of the rains occurs about the 12th week during the short rainy season and 10th week for the long rainy seasons (Biamah et al., 1998). The end of the rainy season is expected when a trend of persistent one rain day per week is experienced and when the daily rainfall is much less than the expected daily evaporation rate (Biamah et al., 1998).

Table 4. Test of equality values for the means and variances during the long and short rainy seasons in Kibwezi and Iiuni, Kenya.

Season	Station	n	\bar{x}	s^2	F_{cal}	F_{tab}^{\dagger}	t_{cal}	t_{tab}^{\ddagger}
Long Rains	Kibwezi	55	2.87	107.73	1.59	2.15	0.11	± 1.95
	Iiuni	16	3.17	67.73				
Short Rains	Kibwezi	55	5.00	162.44	1.68	2.15	0.07	± 1.95
	Iiuni	16	4.75	96.63				

[†] 'F' test at 5% level of significance, and 54 and 15 degrees of freedom respectively.

[‡] 't'-test at 5% level of significance and 69 degrees of freedom.

This analysis of annual, seasonal and monthly rainfall variations in Iiuni watershed has shown that annual rainfall variations are low, seasonal rainfall variations are slightly higher (a bit more for the long rains than for the short rains), while monthly rainfall values have the highest variability.

The test of equality of means and variances of daily rainfall data from Kibwezi ($n = 55$) and Iiuni ($n = 16$) stations were done using the 't' and 'F' tests (at 5% level of significance) respectively. The results obtained (Table 4) accepted the null hypotheses of equality of means ($H_0: \mu_1 = \mu_2$) and variances ($H_0: \sigma_1^2 = \sigma_2^2$). These tests confirmed the similarity of rainfall characteristics between the two stations, and justified the use of Kibwezi data for the stochastic drought analysis.

2.3.2 Stochastic behavior of spells and rainfall amounts

The values of the probability parameters, q , qq , pp , $E(x)$ and $V(x)$, that were used in simulating the longest dry and wet spells and largest rainfall amounts, were estimated from the daily rainfall data of Kibwezi ($n = 55$) station. The estimated values of probability parameters were for the long and short rainy seasons (Table 5).

Table 5. Seasonal values of dry and wet spell and rainfall amount parameters of Kibwezi, Makueni District, Kenya.

Parameter	Long rains	Short rains
q	0.83	0.68
pp	0.51	0.64
qq	0.89	0.80
$E(x)$ (mm)	2.86	5.00
$V(x)$ (mm ²)	107.73	162.44
A	0.78	0.78
B	22.96	37.52

The longest dry and wet spells and largest rainfall amounts in Iiuni were analyzed to establish if there was a Markovian dependence. This analysis was done by comparing the CDFS of predicted and observed data. From the results obtained (Fig.s 3, 4 and 5), the spells and rainfall amounts showed a Markovian persistence or dependence. Markovian persistence or dependence is judged by the closeness of observed data points to the predicted data trend line. For example, the dry and wet spells and rainfall amounts during the long rains showed better persistence than the dry and wet spells and rainfall amounts during the short rains (Fig.s 3, 4 and 5). Similar results were obtained when the transitional matrices (1) and (2) were compared. During the analysis, more than 80% of the runs displayed the behavior of being Markovian. Thus, this confirms the reliability of Kibwezi parameters in validating the Markovian persistence of Iiuni rainfall data. The CDFS show that the Markov model is appropriate for predicting the longest dry and wet spells and largest rainfall amounts in semi-arid environments of Kenya.

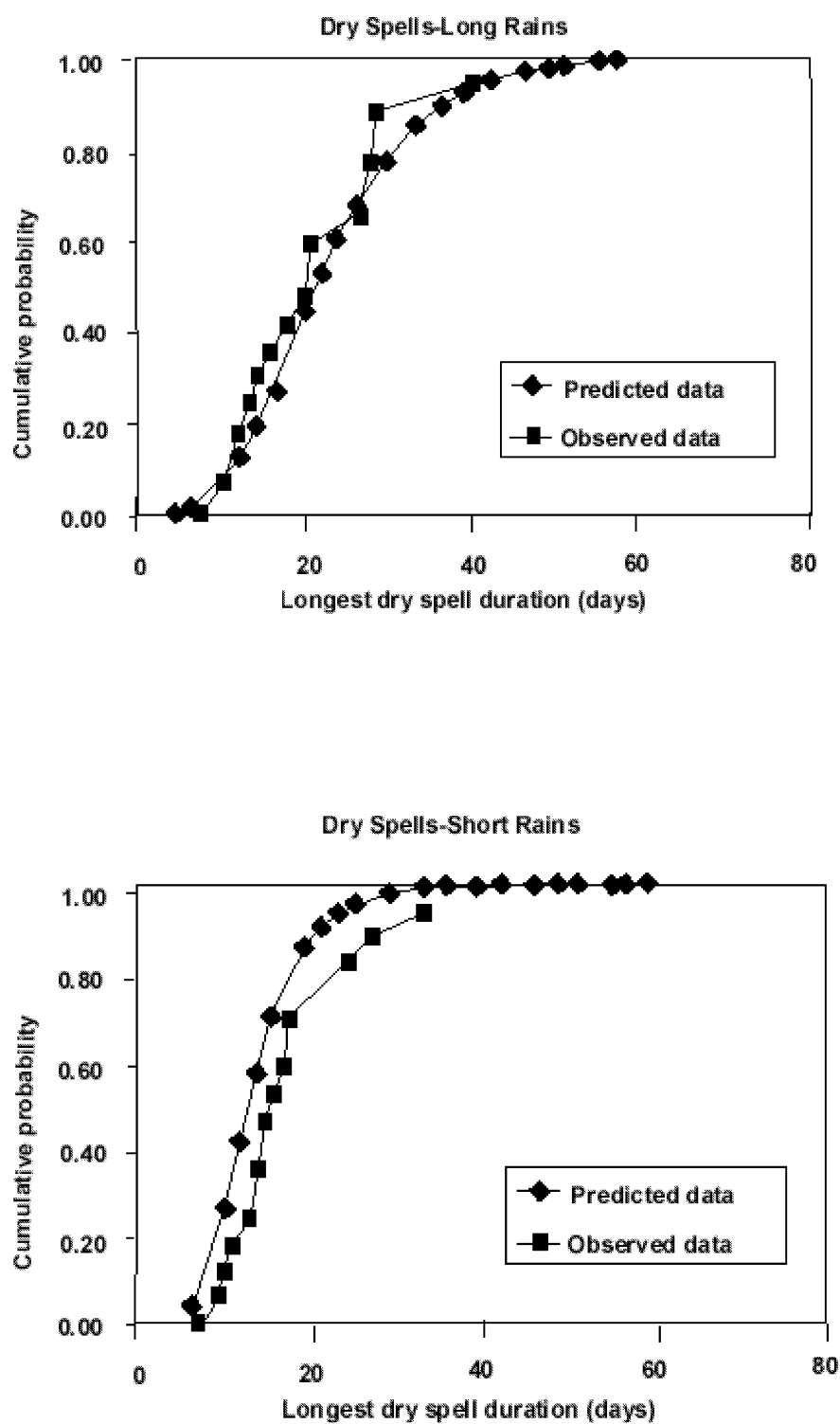


Figure 3. The CDFS of longest dry spells in Iuni watershed, Machakos District, Kenya.

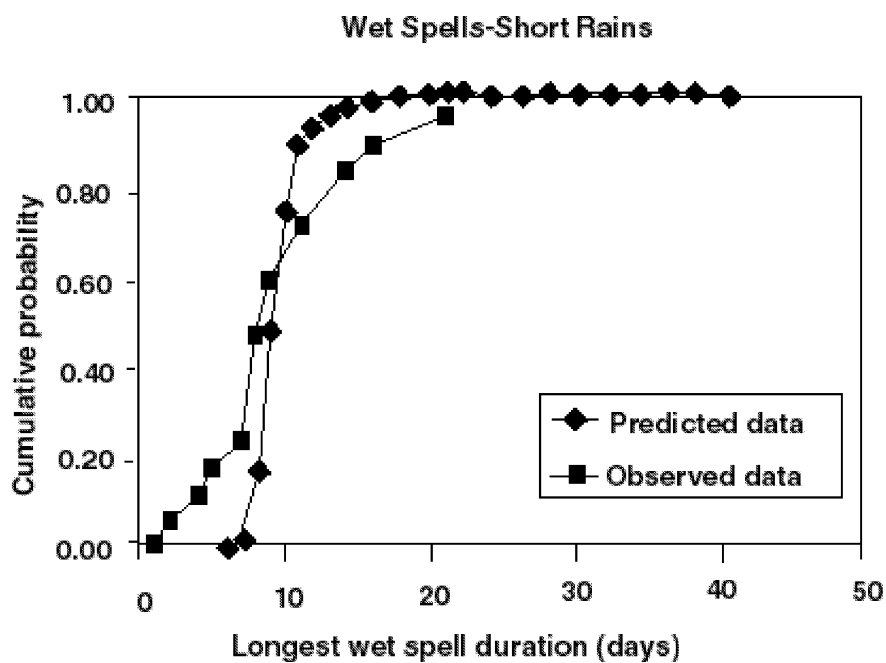
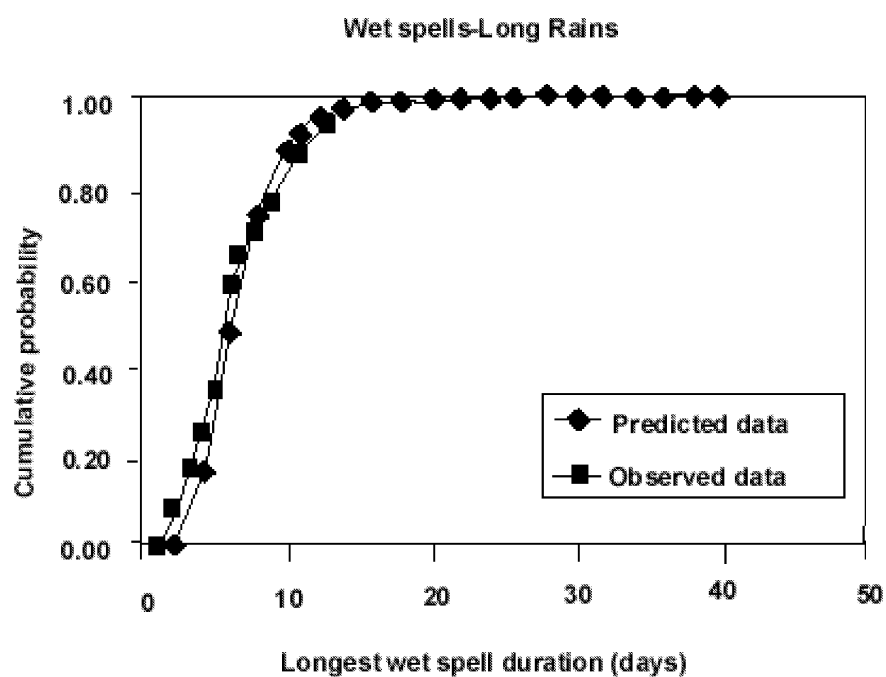


Figure 4. The CDFS of longest wet spells in Iiuni watershed, Machakos District, Kenya.

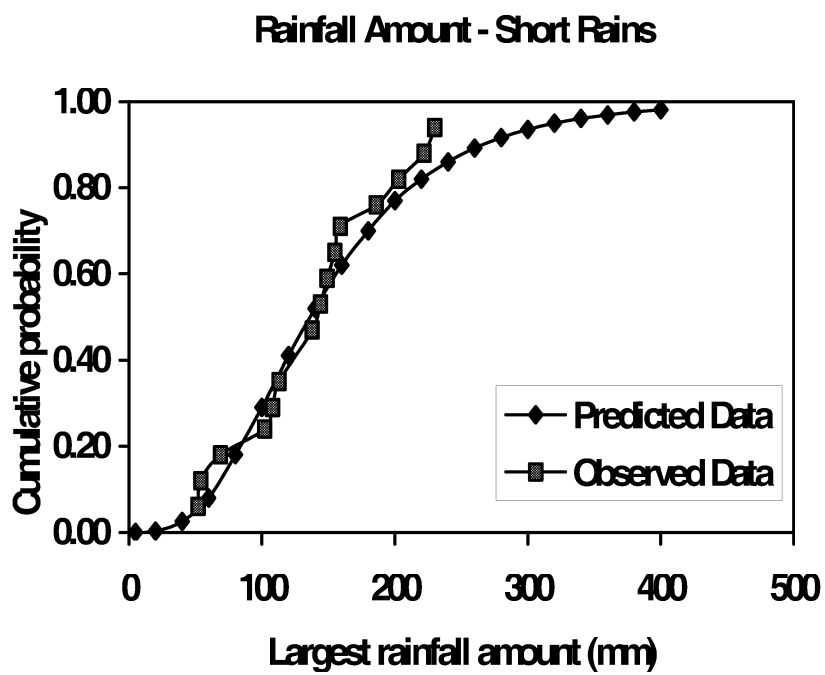
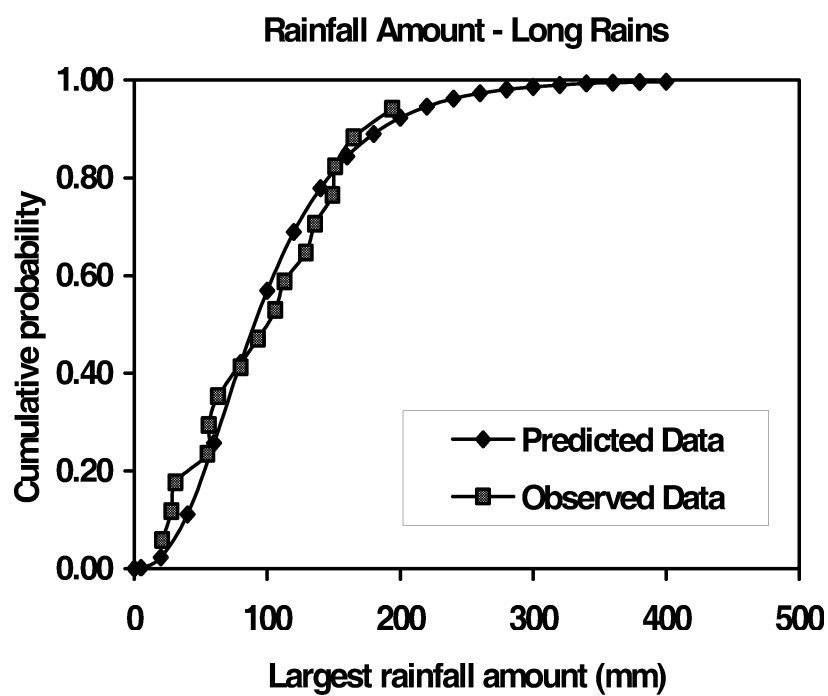


Figure 5. The CDFS of largest rainfall amounts in Iiuni watershed, Machakos District, Kenya.

Table 6. Probabilities of exceedence of dry spells during the long and short rainy seasons in Iiuni watershed, Machakos District, Kenya.

Duration (days)	Probability of exceedence (%)	
	Dry spells – long rains	Dry spells – short rains
60	1	0
50	2	0
40	8	0
30	22	1
20	56	13
10	93	74
6	98	96

Table 7. Probabilities of exceedence of rainfall amounts during the long and short rainy seasons in Iiuni watershed, Machakos District, Kenya.

Rainfall amount (mm)	Probability of exceedence (%)	
	Long rains	Short rains
400	0	2
380	0	2
360	0	3
340	1	4
320	1	5
300	1	6
280	2	8
260	3	11
240	4	14
220	5	18
200	8	23
180	11	30
160	16	38
140	22	48
120	31	59
100	43	71
80	59	82
60	74	92
40	89	97
20	98	100

The seasonal probabilities of exceedence derived from the CDFS of Iiuni watershed are presented in Tables 6 and 7. Generally, during the long rainy season, there is a higher probability of occurrence of longer dry spells and smaller rainfall amounts when compared with the short rainy season (Table 6). For example, the duration of a dry spell with an exceedence level of 80% is 14 days during the long rains and 9 days during the short rains. Similarly, the probability of occurrence of rainfall amounts with an exceedence level of 59% is 80 mm for the long rains and

120 mm for the short rains (Table 7). The mean and variance values of dry and wet spells and rainfall amounts

Table 8. Statistics for the longest dry and wet spells and largest rainfall amounts based on predicted data in Iiuni watershed, Machakos District, Kenya.

Parameter	Long rains		Short rains	
	Dry spell (days)	Wet spell (days)	Dry spell (days)	Wet spell (days)
Mean	24	5	12	6
Variance	120	4	33	9
Largest rainfall amount (mm)				
Rainfall amount at 50% exceedence probability	91		136	
Rainfall amount at 80% exceedence probability	53		85	

are shown in Table 8. Based on the mean values of observed data of Iiuni watershed, the longest dry spells are expected to last for 24 days (about 3.5 weeks) during the long rains and 12 days (about 2 weeks) during the short rains. The largest rainfall amounts at 50% exceedence probability (median) are 136 mm for the short rains and 91mm for the long rains. This analysis has confirmed that the short rains are more reliable for crop production than the long rains in Iiuni watershed.

2.4 Conclusions

An analysis of variance (ANOVA) carried out on Iiuni rainfall data established that annual and seasonal rainfall variability between the stations in Iiuni watershed is not significant and hence Iiuni station's daily rainfall data was used to represent the rainfall features of the entire watershed in this study. ANOVA has also shown that for semi-arid environments with topographic variations similar to Iiuni, one rain gauge per 12 km² can be regarded as satisfactory. An ANOVA established the equality of means and variances implying that Kibwezi and Iiuni stations have similar rainfall characteristics. Therefore, the probability parameters obtained from the long-term rainfall data of Kibwezi were used in this drought analysis for Iiuni watershed.

The monthly rainfall analysis of the two rainy seasons showed high variability of monthly rainfall and that the six driest months in Iiuni are January to February and June to September. There was also significant monthly variability in rainy days. On a monthly basis, the analysis showed that approximately 91% of the expected seasonal rainfall amount occurred in the first two months after the onset of the rains. Thus any tillage practices recommended must ensure the effectiveness of rainfall in this critical period of two months.

The Markov model performed well in simulating the longest spells (runs) and largest rainfall amounts during the short and long rainy seasons in Iiuni watershed. The graphical comparison of

predicted and observed CDFS of spells and rainfall amounts provide the best means of establishing if there is a Markovian dependence in line with the findings of Sharma (1996). The median values of probability parameters based on the daily rainfall data from Kibwezi station were used in these predictions.

The dry and wet spell analysis based on the probability parameters from Kibwezi rainfall data has shown that dry spells last for 24 days during the long rains and 12 days during the short rains. For the wet spells, their duration may vary from 5 days during the long rains to 6 days during the short rains. Also total rainfall amount expected during the extended wet spell periods are 91 mm for the long rains and 136 mm for the short rains.

The longest dry spell analysis is of practical relevance to the selection of the best conservation practices (including conservation tillage) for the management of Iiuni watershed. The largest rainfall amount analysis can be used to determine the watershed runoff volume and discharges that would assist in the design of flood and erosion control structures, and the design of runoff water catchment systems (RWCS), which are essential for supplementary irrigation in semi-arid Kenya.

If a runoff water catchment system is to be designed for a probability of exceedence level of 50%, then the design values of rainfall amount are 91 mm for the long rains and 136 mm for the short rains. Thus the best conservation practices and RWCS should be designed according to the longest dry spell and the largest rainfall amount respectively.

The statistics from this analysis have shown that the short rains (October to December) are evenly distributed, reliable and adequate for crop production. On the contrary, the long rains (March to May) are poorly distributed, unreliable and inadequate for crop production. Also severe drought episodes are less likely to occur during the short rains.

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Chapter 3

Tillage methods and soil and water conservation in Eastern Africa

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Tillage methods and soil and water conservation in Eastern Africa

Abstract

This paper reviews some research studies on tillage methods influencing soil and moisture conservation in the eastern African countries of Kenya, Tanzania, Malawi and Ethiopia during the past four decades (1950-1990). Most of these studies were conducted in marginal rainfall (semi-arid) areas and on shallow soils of various textures (sandy clay loam, sandy clay, clay and loam). The studies were meant to establish the effects of tillage and residue management practices on physico-chemical soil properties (i.e. structure, bulk density, soil moisture and organic matter contents), runoff and infiltration. This review emphasizes the importance of appropriate tillage and residue management methods (contour bunds and terraces, minimum tillage, tied ridging, mulching and conventional tillage) in providing soil conditions favorable for soil moisture conservation and subsequent crop performance and yield on smallholder farms.

3.1 Introduction

3.1.1 General background

The primary objective of any tillage operation should be to optimize soil conditions such as bulk density, pore size distribution, temperature, consistency, soil water intake rate and moisture retention capacity for increased crop production through appropriate and timely seedbed preparation and weed control.

Most smallholder farmers in eastern Africa use traditional methods of seedbed preparation and weed control (i.e. hand hoeing, slash and burn). In practice, timely seedbed preparation using these methods is difficult to achieve especially where ground-breaking operations require high energy inputs. The occurrence of soil surface hardpans has often delayed tillage operations up to the onset of the rains when soil moisture conditions would be favorable. High labor demands during this peak period have delayed seedbed preparation operations and consequently affected soil productivity. Furthermore, soil productivity is threatened by shallow digging (causing subsurface hardpans) and soil erosion hazards (owing to tillage operations on steep slopes and highly erodible soils) that are quite evident on fragmented smallholder farms.

In marginal rainfall areas of eastern Africa, recurrent low soil moisture conditions have been attributed to low infiltration of rainwater (owing to soil surface sealing and crusting properties) and organic matter content of the soils. Rainfall impact causes surface sealing and crusting of bare soils resulting in very high runoff water losses. It is this runoff water that must be harnessed and conserved in the soil to sustain crop growth. This calls for appropriate tillage practices that not only improve rain penetration but also conserve adequate soil moisture for plant growth. Current conservation tillage practices used in these areas include contour bunds and terraces, minimum tillage, conventional tillage, residue mulching and tied ridging.

Conservation tillage research studies in eastern Africa have focused on the effects of these tillage practices on soil and moisture conservation for increased crop production. These studies have attempted to develop appropriate and sustainable tillage and residue management methods that would maintain favorable soil conditions for good plant growth on small-scale farms. To be

successfully adopted by smallholder farmers, conservation tillage methods must offer tangible benefits through increased crop yields, fuel wood and fodder production. These tillage methods, whilst adapted to area specific soils conditions, should also be well designed to cope with the high rainfall intensities, high erodibility of soils and high temperatures prevailing in the region. The new conservation farming techniques must be closely knit within the existing fabric of traditional farming practices like mulching, ridging, mixed cropping, crop rotation and shifting cultivation and should be socio-economically acceptable to smallholder farmers.

3.1.2 Environmental aspects

Climate

The seasonal rainfall patterns are governed by the seasonal shifts and intensity of the low pressure Inter Tropical Convergence Zone (ITCZ). In eastern Africa, rainfall occurrence is primarily bimodal with two distinct rainy seasons (short and long rains). Semi-arid areas receive average annual rainfall of 800-1000 mm. The short rains account for about 65% of the total annual rainfall. Potential evaporation ranges from 1450 to 2200 mm y⁻¹. The rainfall though low and erratic, occurs in high intensities of short duration and is highly erosive. High amounts of runoff are often generated from these storms owing to inherent low infiltration rates of the soils. Concentrated runoff flows are responsible for the severe erosion that occurs in these marginal rainfall areas.

Soils

The most dominant soils in marginal rainfall areas of eastern Africa are Luvisols, Acrisols and Vertisols. Except for the Vertisols, the other two soils are characterized as shallow soils with inherent low organic matter, water retention capacity, salt and sodium content and strong surface sealing and crusting properties. The dominant clays of Luvisols/Acrisols are usually of the 1:1 ratio (kaolinite). Water infiltration in the soils is rather low, especially in the B-horizons which generally have a heavy texture. The management of these soils requires deep plowing (to break the crust and subsoil hardpans) and addition of organic matter content from residue mulch or organic manure. Luvisols/Acrisols are often cropped during the rainy season. Vertisols are characterized as deep soils having moderate to high salt and sodium content, montmorillonitic (2:1) clay mineralogy, and low infiltration rates (owing to swelling when wet). Structural tillage practices are not feasible on Vertisols owing to their unstable structure (2:1 clays). Vertisols are usually cropped after the rainy season.

Overall, tillage management requirements of these three soils would depend on clay mineralogy, workability, moisture holding capacity and other soil characteristics. Luvisols/Acrisols have a compact subsoil layer (argillic horizon) owing to an increase in clay content from A to B. These soil problems (especially the sealing and crusting) are known to affect seedling emergence, decrease rain infiltration and consequently result in high surface runoff rates (with minimal soil loss unless the soils are disturbed and have a cloddy top soil structure). Vertisols, owing to their swelling and shrinking properties, affect crop root development when dry and infiltration when wet. These soils are workable immediately after the rainy season (under optimum soil moisture conditions) when the soils are loose and crumbly and hence requiring low draught per unit area.

Cropping systems

The major crops grown in semi-arid areas of eastern Africa include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cowpeas, groundnuts and cotton. Crop performance and yield are significantly influenced by the amount of rainfall and distribution throughout the rainy season. As a result of inherent soil moisture deficits, the period of cropping is limited to the rainy season. The potential length of growing season as determined by the long and short rains influences the choice of crops in these areas. Most crops are grown during the short rains since more rainfall occurs within this period. Intercropping is a very common farming practice as it minimizes the risks of crop failure owing to unexpected soil moisture deficits. Usually combinations of two or three crops are evident in most of these areas.

Socio-economic aspects

During the past two to three decades, human and livestock population in semi-arid areas of eastern Africa has significantly increased and consequently led to an over exploitation of the limited land and water resources. Soil and vegetative degradation have become widespread owing to overgrazing, deforestation, burning and over-cultivation. Accompanying this unprecedented population increase is the fragmentation of landholdings and sedentarization of pastoralists, which has destabilized the very fragile ecology of the areas. This has adversely affected food and fodder production and left the entire population vulnerable to food and fiber shortages. Unpredictable weather conditions have exacerbated the problems and further decreased the production potential of the resource base.

3.1.3 Tillage methods

Traditional tillage and residue management methods that are widely practiced in this region include slash and burn, residue mulching, ridging, mixed cropping, conventional tillage (hand hoeing), crop rotation and shifting cultivation. Additionally, new conservation tillage methods like minimum tillage (no till), terracing, cover cropping, intercropping, contour buffer stripping, tied ridging, contour bunding and plowing have been introduced to optimize soil conditions for improved crop performance and yield. Most of these traditional and new tillage operations involve high-energy inputs (labor intensive, use of hand tools) both in construction and maintenance.

The applicability of tillage practices depends on soil properties, climatic conditions, types of crops to be grown and socio-economic conditions of the beneficiaries (smallholder farmers). For instance, contour bunds and ridges have proven to be very effective in marginal rainfall areas where rainfall intensities and runoff rates are high. These structures are recommended for stable soils with surface sealing and crusting properties and low water intake rates. Contour bunds and ridges are expected to impound the runoff and increase the infiltration opportunity time of the soil.

In conventional tillage, farmers use hand hoes to break the land up to a depth of 20 cm often leaving large soil clods at the surface. Where the clods are too large and the weeds have grown, harrowing to break the clods and remove the weeds is recommended. Often conventional tillage involves primary tillage operation with no secondary tillage until weed control.

Minimum tillage operations often involve strip tillage (narrow strips of 20 cm width of cut along the planting rows) or spot tillage (where planting holes of size 10 cm x 10 cm are made using hand hoes). Minimum tillage is also practiced using the traditional slash and burn techniques.

Contour buffer strips of widths of 1 to 2 m are often combined with contour ridges to check runoff and soils loss. Tied ridging at 2-3 m spacing along the furrows is usually done before the onset of the rains to avoid any breakages of ridges as a result of concentrated runoff flows.

Crop residues are either placed on the soil surface (to dissipate rain energy and reduce surface sealing effects) or incorporated into the soil (ridges and furrows) as a means of supplementing organic matter deficiencies and improving the water holding capacities of soils.

3.2 Tillage research

3.2.1 Kenya

Tillage research in Kenya has been conducted over the last four decades with the focus of the studies being on tillage methods such as mulching, tied ridging, minimum tillage, conventional tillage and contour furrows. Most of these studies were conducted in marginal rainfall areas where the soils were characterized as having inherent low organic matter content and surface sealing and crusting properties. Rainfall in these areas is quite intense, of short duration and highly erosive.

Within the semi-arid area of Makaveti, Machakos, Pereira and Beckley (1952), conducted a pasture improvement study and found that the infiltration rate of a Luvisol (FAO/UNESCO Classification) improved when its soil surface crust was broken through contour plowing, ridging and ripping. The best pastures were obtained by contour plowing and ridging with incorporation of a small dressing of cattle manure. Plowing and ridging conserved moisture, but deep ripping did not assist in grass establishment under the low rainfall conditions of the experimental site.

In the same area, Pereira et al. (1954) conducted a crop rotation study in which infiltration rates were comparatively low after 1 year of uniform cropping. The rotation of grasses, cover crops and cultivated crops over a 3 year period had some short term improvements on soil structure.

In an experiment in a drier area of Kenya, Pereira et al. (1954) found that a 10 cm mulch of elephant grass in a coffee plantation produced after 2 years an infiltration rate equal to that of 5 years under elephant grass.

Pereira et al. (1958) in a water conservation study in a semi-arid area established that tied ridges do not improve the resistance of soil to surface sealing, but may impede surface flow of water within the furrow, thus allowing more time for water to infiltrate.

Pereira and Jones (1965) found that clean weeding caused an average of 15% reduction in infiltration during very heavy storms compared with minimum weeding or the incorporation of grass mulch into the soil during cultivation.

Robinson et al. (1965) found that mulching increased total pore space, free drainage and rainfall acceptance by 8%, 9% and 53%, respectively on a latosol in a coffee growing area of Kenya.

Pereira et al. (1967) studied soil and water conservation systems for high rainfall areas of Kenya. The study established that contour plowing (using Nichols terraces) and tied ridging of a Kikuyu red loam soil (Nitisol, FAO/UNESCO Classification) on slopes of 10%, effectively controlled soil and runoff water losses. Runoff was heaviest from well-established grass leys (*Cynodon dactylon*) immediately after intensive grazing and subsequent trampling by livestock and when exposed to rainfall intensities exceeding 50 mm h⁻¹. The trampling effects at the site were

transient with variable runoff rates. Soil surface profiles at the experimental site showed remarkable slope stability under intensive tillage. Furthermore, some benching effect was noted on fields under contour cultivation. High soil loss and runoff rates were observed where ridging and tying operations were undertaken at different times. Where both operations were done at the same time, the tied ridges effectively controlled runoff and reduced soil loss. At the same site, soil moisture measurements (using gypsum blocks) were taken at 0.6, 1.2, 1.8, 2.4 and 3 m depths for two terrace spacings (1.5 and 6 m vertical intervals) on 10% slopes. There were no significant differences in the availability of soil moisture between the two treatments. Soil moisture extraction patterns of star grass (*Cynodon dactylon*) showed extensive root development to 3 m depths 9 months after planting. Over the 2 year period of soil moisture measurements, moisture deficits occurred when rainfall was less than the consumptive use of *Cynodon dactylon* (Table 1).

Table 1. Water consumption by star grass (*Cynodon dactylon*) (after Pereira et al., 1967).

Days after planting	Rainfall (mm)	ET _o [†] (mm)	SMC [‡] (mm)	ET _c [†] (mm)	ET _c /ET _o ratio
91	80	493	-54	153	0.31
178	231	536	+67	163	0.30
319	263	537	-32	295	0.55
412	33	272	-110	143	0.53
493	298	434	+51	248	0.57
567	320	386	+130	191	0.49
608	37	148	-65	102	0.69
733	75	484	-91	166	0.34

[†]ET_o - Reference crop evapotranspiration; ET_c - Actual crop evapotranspiration.

[‡]SMC - Soil moisture change.

In a tillage study at Katumani, Machakos, Marimi (1978) found that minimum tillage, conventional tillage and tied ridging operations on a sandy clay soil (chromic Luvisol, FAO- UNESCO Classification) broke the soil surface crust and improved infiltrability and moisture storage of the soil. Higher soil moisture contents were obtained under tied ridges when compared with the other tillage methods (Table 2). Minimum tillage stored the least amount of soil moisture. Significantly higher dry matter and grain yields of maize and beans were obtained in tied ridged plots as compared to the other plots (Table 3). Minimum tillage gave the lowest crop yields. During the study period, runoff occurred on two occasions from minimum and conventional tillage when rainfall exceeded 15 mm. This confirmed that soil surface sealing occurred rapidly even with light rains.

Table 2. Effect of tillage methods on soil moisture content at end of short rains period, 1976/1977 (after Marimi, 1978).

Soil depth (cm)	Soil moisture content (% volume)				
	Minimum tillage	Conventional tillage	Tied ridging	SE†	PWP‡
0-30	15.7	16.1	17.9	0.52	19.0
30-60	19.7	19.4	21.9	0.55	20.3
60-100	19.6	19.0	21.1	0.36	20.6
100-150	16.3	16.5	16.7	0.21	19.9

†SE - Standard error.

‡PWP - Permanent wilting point.

Table 3. Effect of tillage methods on crop yield (after Marimi, 1978).

Period	Crop	Crop yield (kg ha ⁻¹)			
		Minimum tillage	Conventional tillage	Tied ridging	SE†
Long rains	Maize (dry matter)	1068	1047	1105	63
Short rains	Maize (dry matter)	2040	1920	1760	0.09
	Maize (grain yield)	337	221	513	51

†SE - Standard error.

Onchere (1977), in an infiltration study at Kitale, found that bare fallow, minimum tillage and conventional tillage operations on an orthic Luvisol (FAO/UNESCO Classification) at a slope of 3%, significantly improved infiltration and other soil properties. It was observed that the method of seedbed preparation significantly influenced the pore size distribution and density, moisture holding capacity, bulk density and surface sealing and crusting properties of the soil. Whereas the coarse seedbed had no crusted soil surface, the other seedbeds showed some crusting. Bare fallow had the least crusted soil surface. From the moisture characteristic curve (Fig. 1), a coarse seedbed absorbed more water than the other treatments and hence had the highest moisture holding capacity (9.1% by volume). Njihia (1979) at Katumani, Machakos monitored the effects of tied ridges, conventional tillage, crop residue mulch and farmyard manure on soil and moisture conservation. These tillage practices were tested on red sandy clay soil (chromic Luvisol, FAO/UNESCO Classification) at a slope of 12%. The soils had strong surface sealing and crusting properties and an average bulk density of 1.25 g cm⁻³. Maize stover mulch was sufficiently effective in controlling runoff through increased surface water storage.

The storage increased the time available for infiltration. Maize stover also helped minimize evaporation and surface sealing and crusting. Tied ridges effectively controlled runoff even from a maximum storm of 70 mm per day (with a return period of 3 years). Conventional tillage with or without farmyard manure lost about 40% of the storm rainfall (Table 4). A grain yield of maize was

realized from the tied ridged and stover mulch plots for a seasonal rainfall of 171 mm. No grain was harvested from conventional tillage with or without farmyard manure.

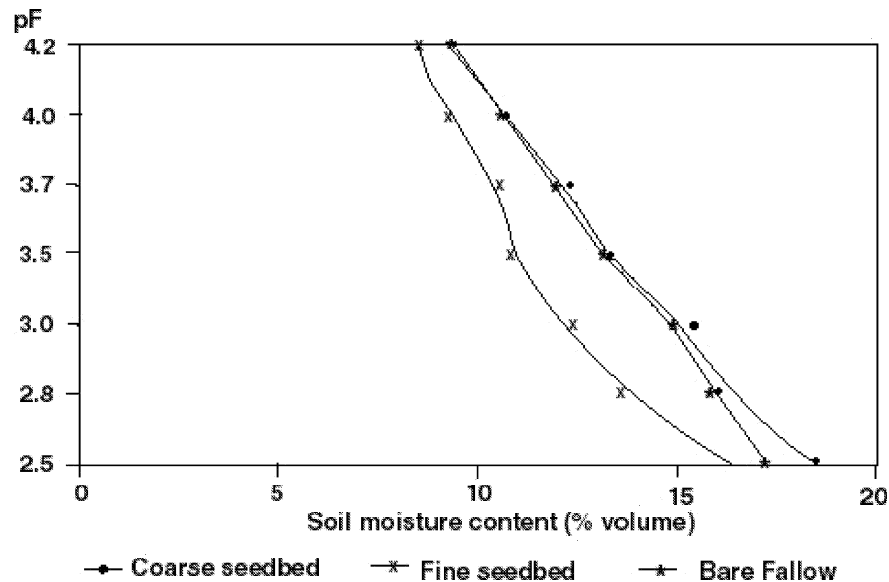


Figure 1. Topsoil moisture characteristic curves of selected tillage practices (after Onchere, 1977).

Table 4. Soil moisture and runoff arising from 122.1 mm rainfall (after Njihia, 1979).

Treatment	Soil moisture storage (mm)	Runoff (%)
Stover mulching	122.1	-
Tied ridging	86.0	13.7
Farmyard manure	69.0	38.0
Conventional tillage	65.8	42.7

Othieno (1980) at Kericho found that mulching effectively controlled water vapor losses from the soil. The application of straw mulch with a thickness of 5 cm reduced evaporation significantly from 0 to 35 cm soil depth during a hot, rainless 10 days period.

Muchiri and Gichuki (1982) at Katumani found that contour furrows were effective in controlling surface runoff and subsequently conserving soil moisture in a semi-arid area. The desi-plow used in making contour furrows was reported to produce a much rougher seedbed and a draft requirement, depth of tillage and rate of work comparable with the moldboard plow.

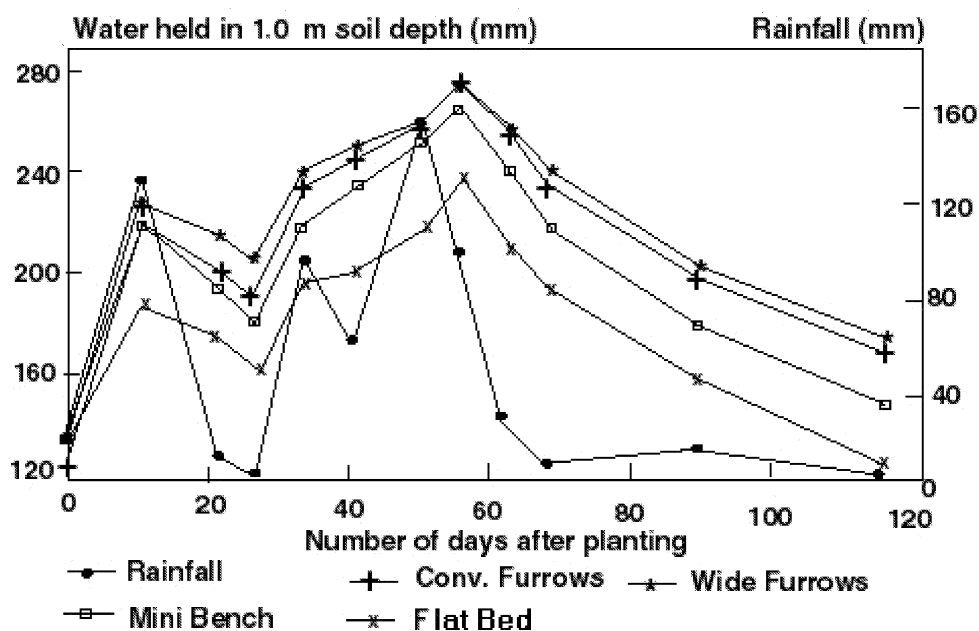


Figure 2. Rainfall distribution and variation of soil moisture content with tillage method during the short rains period (after Kilewe and Ulsaker, 1983).

Table 5. Effect of tillage method on maize yield (after Kilewe and Ulsaker, 1983).

Tillage method	Maize yield (kg ha ⁻¹)	
	Short rains	Long rains
Flat	3722	256
Conventional furrow	5242	725
Wide furrow	5458	844
Mini bench	4680	643

Kilewe and Ulsaker (1983) at Katumani, found that contour furrows, bench terracing and conventional tillage operations on a sandy clay loam (ferral-chromic Luvisols, FAO/UNESCO Classification) effectively controlled runoff and conserved soil moisture. The study showed that conventional furrows, wide furrows and mini benches retained all the runoff within the furrows and increased infiltration opportunity time after the rainfall. Wide furrows (1 m wide) had the highest soil moisture content followed by conventional tillage during both the short and long rains (Fig. 2 and Fig. 3). These furrows had significantly higher maize grain yield than all the other tillage methods (Table 5).

In a tillage study at Embu, Ngugi and Michieka (1986) monitored the effects of conventional tillage and two minimum tillage operations (strip and spot tillage) on brown clays (eutric Nitisols, FAO/UNESCO Classification). The soils had a low organic matter content (1.66%) and were located in a medium rainfall area (1081 mm). The study showed that conventional tillage

had the best crop performance and yield (Table 6) when compared with the other tillage methods during both rainy seasons (short and long rains).

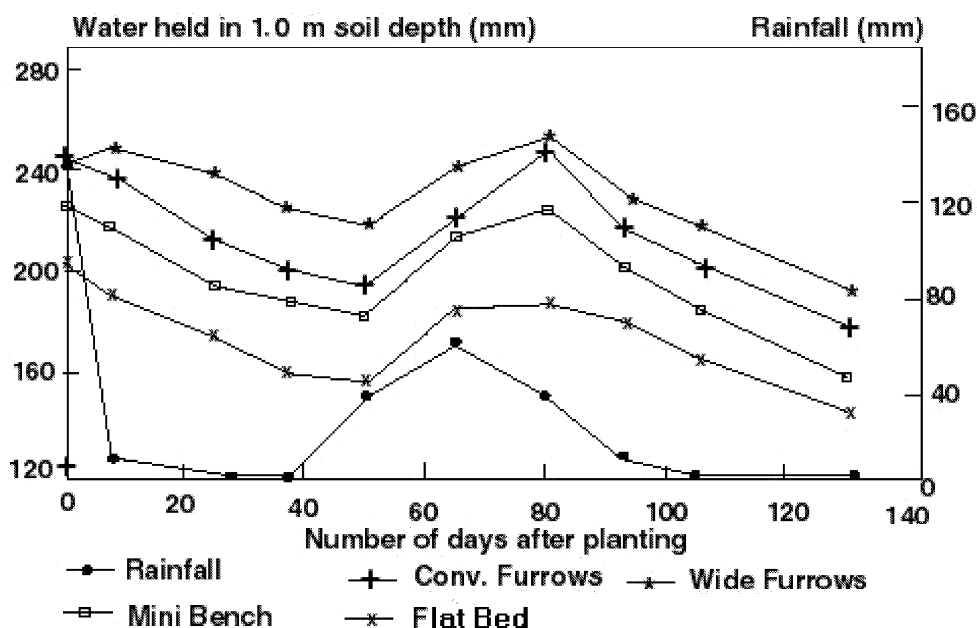


Figure 3. Rainfall distribution and variation of soil moisture content with tillage method during the long rains period (after Kilewe and Ulsaker, 1983).

Table 6. Effect of tillage methods on maize grain yield (after Ngugi and Michieka, 1986).

Tillage method	Maize grain yield (kg ha ⁻¹)			
	Short rains	LSD† (0.05)	Long rains	LSD† (0.05)
Conventional tillage	3380	1.00	6060	1.09
Strip tillage	3330	1.00	5790	1.09
Spot tillage	3340	1.00	4650	1.09
SE† (treatment means)	0.118		0.114	

†LSD - Least significant difference; SE – Standard error.

Liniger (1989) observed that the reduction of runoff and evaporation loss was a significant factor in mulched plots. Consequently the maximum storage of plant available water was between 45 and 110% higher in the mulched plots than under conventional tillage. Mulching was also reported to have increased maize yields by 4.5 times when compared with similar yields under conventional tillage.

In Kalalu, Laikipia, Gicheru (1990) monitored the effect of conventional tillage, tied ridging and crop residue mulching on soil moisture conservation under marginal rainfall (750 mm) conditions. The experiment was carried on a clay soil (ferric Acrisols, FAO/UNESCO Classification; Table 7) at a slope of 2%. This study showed that crop residue mulching (despite lagging behind in seedling

emergence) did conserve more moisture and had the best crop (maize and beans) performance and yield when compared with the other two tillage practices (Tables 8, 9, 10). The tied ridged plots had the lowest amount of soil moisture (Tables 8 and 9) and hence the poorest crop performance and yield (owing to no runoff to impound and high evaporation water losses from increased soil surface area) (Table 10).

Table 7. Soil profile characteristics of a ferric Acrisol, Kalalu, Laikipia (after Gicheru, 1990).

Soil depth (cm)	Bulk density (g cm ⁻³)	Soil texture†	Organic matter (%)	Field capacity (% volume)	Permanent wilting point (% volume)	Available moisture (% volume)
0-30	1.3	C	2.0	43.6	35.7	7.9
30-60	1.2	C	1.7	45.2	27.9	16.3
60-90	1.3	C	0.7	39.2	31.3	7.9
90-120	1.4	C	0.7	36.1	32.1	4.0

†C - Clay.

Table 8: Cumulative soil moisture for beans, short rains period, Kalalu, Laikipia (after Gicheru, 1990).

Crop stage	Cumulative soil moisture content (% volume)		
	Residue mulch	Conventional tillage	Tied ridging
Emergence	27.6	30.6	27.4
Budding	25.6	25.6	25.6
Flowering	21.3	21.2	15.3
Maturity	10.0	13.9	6.0
Harvesting	5.5	8.9	0.7

Table 9. Cumulative soil moisture for maize, long rains period, Kalalu, Laikipia (after Gicheru, 1990).

Period after planting (weeks)	Cumulative soil moisture content (% volume)		
	Residue mulch	Conventional tillage	Tied ridging
3	10.3	14.3	0.2
7	19.6	0.8	4.4
11	147.6	148.8	131.4
14	2.3	6.1	3.8

Table 10. Average grain yields of maize and beans, Kalalu, Laikipia (after Gicheru, 1990).

Crop	Average grain yield (kg ha ⁻¹)		
	Residue mulch	Conventional tillage	Tied ridging
Maize	1083.3	850.0	833.3
Beans	936.1	922.2	683.3

3.2.2 Tanzania

Research on tillage methods in Tanzania has been conducted over the past three decades or so. The studies have concentrated on the effects of tied ridging, mulching, zero tillage and conventional tillage operations on soil moisture conservation, crop performance and yield. The experimental sites were located in low rainfall areas with significant soil moisture deficits.

Peat and Brown (1960) while conducting an experiment in the Lake Province of Tanzania found higher crop yields of cotton and sorghum from tied ridges than from conventional tillage in most years, and sometimes the yield doubled. However, in high rainfall seasons there were no significant yield differences recorded.

Dagg and Macartney (1968) in an experiment within Jaro Valley, showed that tied ridging was quite effective in conserving water and enhancing the soil moisture holding capacity. Macartney et al. (1971) at Kongwa, Central Tanzania, reported better crop yield from tied ridging as well.

Huxley (1979), at Morogoro, monitored the effects of zero (minimum) tillage, mulching and conventional tillage on crop production. The results showed that maize yields obtained from zero tillage were about 65-75% of those from conventional tillage. The incorporation of mulch increased maize yields by 18-54%. Generally grass mulch was more effective in conserving soil moisture and increasing crop yields than woody mulch (Table 11).

Table 11. Effects of tillage and mulching on crop yields (after Huxley, 1979)

Crop	Crop yield (kg ha ⁻¹)					
	Zero tillage	Conventional tillage	LSD† (0.05)	Grass mulch	Woody mulch	LSD† (0.05)
Maize	1080	1600	0.137	1600	1420	0.238
Cowpea	471	591	0.040	570	520	0.054

†LSD - Least significant difference.

Other investigations on zero tillage by Khatibu and Huxley (1979) at Morogoro, showed some significant cowpea yield increases in tilled systems (1069 kg ha⁻¹) when compared with no till systems (869 kg ha⁻¹).

Masseri and Jana (1979) at Morogoro found that conventional tillage, zero tillage, strip tillage and grass mulching (4 t ha⁻¹) operations on a sandy clay loam soil (Ferralsol, FAO/UNESCO Classification) with an organic matter content of 3.5% and a top soil bulk density of 1.4 g cm⁻³, resulted in varying average soil moisture contents for 0-90 cm soil depths. At 68 days after planting, soil moisture was highest in conventional tillage plus mulch and decreased in the order of strip tillage, zero tillage and conventional tillage (Table 12). The soil moisture content at 109 days was in the order of strip tillage, conventional tillage plus mulch, conventional tillage and zero tillage.

Jones and Mitawa (1986) established that cereal crops on tied ridges with crop residue mulch performed better than those on open ridges without residue mulch. This good crop performance was attributed to adequate soil moisture conservation in the mulched plots.

Table 12. Effect of tillage on soil moisture and crop grain yields (after Masseri and Jana., 1979).

	Soil moisture content (% volume)				Grain yield (kg ha ⁻¹)			
	Growing days				Crops			
	68	109	118	144	Maize	LSD† (0.05)	Soy bean	LSD† (0.05)
Conventional tillage	24.4	18.0	16.6	16.7	4215	1238	716	524
Conventional tillage + mulch	26.2	18.7	18.4	17.0	4625	1238	936	524
Strip tillage	25.5	19.5	19.1	16.2	4155	1238	678	524
Zero tillage	25.1	17.9	18.1	16.6	4715	1238	750	524

†LSD, Least significant difference.

3.2.3 Malawi

Biamah (1988) conducted a diagnostic study of existing conservation tillage practices in the Machinga Area of south eastern Malawi. The study involved contour ridges, contour buffer strips, graded terraces, diversion ditches and crop residue mulching operations on medium textured slightly acidic brown to reddish brown sandy clay loams to sandy clays. These soils are predominantly Latosols with a few patches of Vertisols within the dambos (swamplands). The study area receives a mean annual rainfall of 559 mm (unimodal) with a 6-7 months dry season. The entire area has fairly shallow soils with an effective topsoil depth of 10-20 cm and a low organic matter content (0.7-1.5%).

Conservation tillage practices consist of boxed (tied) or plain ridges aligned on the contour with the aid of contour marker ridges and contour buffer strips planted to a variety of productive perennial crops and trees. Box ridging of 2-3 m spacing along the furrows is often done before the onset of the rains. Planting of pigeon peas (*Cajanus cajan*) and pastures (*Rhodes* grass) along the contour marker ridges is used to improve the structure and nutrient status of the soil and also provide the fodder. Contour buffer strips of *Rhodes* grass at widths of 1-2 m are combined with contour ridges to check runoff and soil loss. Crop residue is incorporated into the soil (ridges and furrows) as a means of supplementing deficiencies in organic matter and also improving the water retention capacities of the soil.

Field observations on the effectiveness of these structures, showed that when boxed ridges break during severe storms, runoff-flow down-slope will be intercepted by the buffer strips, its velocity slowed by the perennial vegetation allowing more infiltration opportunity time before finally being checked by the marker ridge. Soil washed out of the cropped area and deposited by the buffer strips, over a period of years would develop into a bench terrace.

The introduction of contour ridges, buffer strips and residue mulching has proven to be a feasible and sustainable conservation alternative to labor intensive and costly physical conservation structures (i.e. diversion ditches and graded terraces). Significant increases in soil moisture and subsequently in grain yields have been obtained from these conservation tillage practices.

Mitchell (1986), in the Lower Shire Valley of Malawi monitored the effects of tied ridges, conventional tillage (on natural slope) and contour bunds (on leveled land) on crop production. The dominant soils in the study area were chromic and pelitic Vertisols (FAO/UNESCO Classification). The annual rainfall in the area was 750 mm, 90% of which fell between November and April.

Field observations showed that traditional cultivation techniques (hand hoeing and planting on flat beds) did not prevent runoff. On newly opened lands, tilled soils maintained coarse crumb structure in the top soil, but which deteriorated to smaller aggregates with some soil capping after 4 years. The smaller aggregates were more prone to erosion by runoff (owing to high surface runoff rates).

Results from this study showed that all the tillage practices (except flat seedbed) on leveled land effectively retained rainwater in the soil. There was a reduction in yields in tied ridged and contour banded plots owing to excessive water storage and consequent water logging (which reduced the nitrogen supply to the crop) (Table 13).

An examination of traditional planting techniques of cotton showed that the method of spot tillage (scooping a ditch of 0.3 m long, 0.25 m wide and 0.1 m deep with a hoe and planting seed uncovered) enabled the crop to germinate successfully after only 12-15 mm of rain when compared with at least 50 mm for conventional planting. It was also observed that floods destroyed cotton sown on ridges whereas the cotton planted on the flat bed was undamaged.

Table 13. Effect of tillage practices on cotton yields (after Mitchell, 1986).

Location	Rainfall (mm)		Treatment	Cotton yield (kg ha ⁻¹)	
	Year 1	Year 2		Year 1	Year 2
Nsangwe	802	484	Conventional tillage on natural slope	1869	1584
			Tied ridges	1607	1206
			Ridges on leveled land	1404	1308
Mphonde	695	537	Conventional tillage on natural slope	1733	941
			Tied ridges	1484	1085
			Conventional tillage on leveled land	1507	1101
			Ridges on leveled land	1560	1135

3.2.4 Ethiopia

Tillage research in Ethiopia that has been reviewed in this paper was conducted over the past decade. The studies monitored the effects of conventional tillage, contour furrows, tied ridging, sub-soiling and zero tillage operations on crop production, runoff, soil and organic matter losses. The experimental sites were located in medium and low rainfall areas with variable soil conditions.

Alem (1986) at Mekele, conducted trials on seedbed preparation methods (conventional tillage, open furrows and tied ridging). Significant maize yield differences were obtained among the treatments with the highest yields (1800 kg ha⁻¹) observed on tied ridges followed by plain ridges (1040 kg ha⁻¹). The lowest yields were obtained from conventional tillage (431 kg ha⁻¹). These results showed that improved seedbed preparation methods were effective in conserving soil moisture and in increasing yields in drought affected areas of Ethiopia.

Zugec et al. (1991) at Horro Aleltu, Nekemte, Wollega, monitored the effect of conventional tillage (20-25 cm), subsoiling (30-35 cm deep) disc harrowing (8-10 cm deep), zero tillage and ridging operations on maize and soya bean production. The experiment was conducted over a 2 year period on a rhodic Ferralsol (FAO/UNESCO Classification) with 4-5% organic matter content. Mean annual rainfall over the 2 year period ranged from 1007 to 1346 mm. The results obtained showed that there were no significant maize yield differences between the treatments in the first

year (1007 mm rainfall). This year, zero tillage performed better than conventional tillage. In the second year (1346 mm rainfall), significant maize yields were obtained. The yields were higher on plowed plots than in the other tillage treatments. This year, ridging had better crop performance than the other tillage practices. Soy bean yields showed significant differences between conventional tillage and subsoiling and also between zero tillage and the other tillage methods.

In the same area, Basic et al. (1991) monitored the effects of conventional tillage (disc plowing and harrowing) operations on soil erosion. The experiment was on an acric Ferralsol (FAO/UNESCO Classification) with a slope of 5%. Results obtained showed that surface runoff, soil and organic matter losses varied with tillage practices (Table 14).

Table 14. Effect of tillage method on runoff, soil and organic matter losses (after Basic et al., 1991).

Tillage method	Runoff (% volume)	Soil loss (t ha ⁻¹)	Organic matter loss (kg ha ⁻¹)
No tillage	39	7.6	370
Up and down slope	40	27.0	1267
Across slope	14	1.1	51

3.3 Conclusions

The semi-arid areas of eastern Africa are characterized by low, erratic and poorly distributed rainfall and problem soils (with strong surface sealing and crusting and low organic matter content). Hence these soils require early seedbed preparation in order to conserve adequate soil moisture for good crop growth. Timely seedbed preparation would facilitate early planting, which subsequently enables crops to get established before the rains subside.

Tillage research work done in this region was conducted in medium to marginal rainfall areas and on shallow soils of various textures (sandy clay loam, sandy clay, clay and loam). The studies showed that both timeliness in planting and the amount of antecedent soil moisture conserved in the soil before planting have a major effect on crop yields. Field observations on tillage and residue management practices showed that conventional tillage practices did not prevent runoff whereas conservation tillage practices effectively controlled runoff and soil loss.

Significant increases in soil moisture and grain yields were observed under conservation tillage practices introduced where terracing was in place. Tied ridges performed poorly under excessive or no runoff conditions. Zero tillage performed poorly under these soil conditions because of high soil crusting and compaction, low rainwater infiltration and subsequent increases in surface runoff generation. Smallholder farmers are primarily interested in tillage practices that improve soil moisture conditions, do not involve high energy inputs and that increase crop production.

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Chapter 4

Tillage and farmyard manure effects on crusting and compacting soils at Katumani, semi-arid Kenya

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